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Inorganic Contaminant Removal from Drinking Water by Reverse Osmosis

Charlotte Harbor Water Associates, Inc.
Harbour Heights, FL

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INORGANIC CONTAMINANT REMOVAL FROM DRINKING WATER BY REVERSE OSMOSIS

by

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Cooperative Agreement
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16. ABSTRACT

Pilot plant studies were conducted on the removal of fluoride, nitrate, arsenic III, and arsenic V by low- (200-psig) and high- (400-psig) pressure reverse osmosis systems. Removal data were also collected on the natural constituents in the feed water: total dissolved solids, hardness, calcium, magnesium, sodium, chloride, and sulfate.

The experimental data show the high-pressure system to be much more effective than the low-pressure system for the removal of all contaminants and natural constituents. The high-pressure system had rejections ranging from 78 to 99 percent, and the low-pressure system from 20 to 85 percent. Rejections varied with the specific contaminants, but the order from best to least was the same for both systems: arsenic V, fluoride, arsenic III, and nitrate. Because of the low rejections, the low-pressure system was able to achieve the EPA maximum contaminant levels when the feed water concentrations were only slightly above them.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, and provide a most vital communications link between the researcher and the user community.

Reverse osmosis has been used successfully for desalting brackish water for many years. This treatment process is effective for the removal of most inorganic substances in water, but data are generally lacking on the specific rejection capabilities of certain contaminants. This report presents the initial results of an investigation on the removal of fluoride, nitrate, arsenic III, and arsenic V from water by high- (400 psig) and low- (200 psig) pressure reverse osmosis treatment systems. Information is also presented on the removal of their general water quality constituents: total dissolved solids, sodium, chloride, sulfate, hardness, alkalinity, color, and total organic carbon.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This research project was initiated to evaluate low- (200 psig) and high- (400 psig) pressure reverse osmosis treatment for the removal of specific contaminants from drinking water. Two reverse osmosis systems, each producing 45,000 gpd of product water, were installed in parallel at the Charlotte Harbor Water Association Treatment Plant and used as pilot plant systems. Pilot tests were conducted for 2 to 5 days in duration using a spiked ground water. Operational data and chemical data were collected to evaluate the performances of the two systems and to determine the removal of spiked contaminants and various natural constituents.

This report presents the results of the first 6 months of testing for the removal of fluoride, nitrate, arsenite (As III), and arsenate (As V). Removals of natural constituents, including total dissolved solids, hardness, calcium, magnesium, sodium, chloride, and sulfate, were also determined. Several operational problems occurred during the testing period that required the pilot systems to be modified, and these problems and system changes are described.

This report was submitted in fulfillment of Cooperative Agreement, RC-805207 by the Charlotte Harbor Water Association under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period August 15, 1977 to February 28, 1980.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

CHWA	-- Charlotte Harbor Water Association
DWRD	-- Drinking Water Research Division, USEPA
EMSL	-- Environmental Monitoring & Support Laboratory, USEPA
EPA	-- U.S. Environmental Protection Agency
EQL	-- Environmental Quality Laboratory
gpd	-- gallons per day
gpm	-- gallons per minute
L/S	-- liters per second
m^3	-- cubic meters
MB	-- membrane barrier (low pressure reverse osmosis system)
mg/L	-- milligrams per liter
NIPDWR	-- National Interim Primary Drinking Water Regulations
PCi/L	-- picocuries per liter
psig	-- pressure per square inch gage
RO	-- reverse osmosis (high pressure reverse osmosis system)
TDS	-- total dissolved solids
TOC	-- total organic carbon
µmho	-- micromhos

SYMBOLS

As	-- arsenic
Ca	-- calcium
Cl	-- chloride
Mg	-- magnesium
SO_4	-- sulfate
NO_3	-- nitrate
$NO_3(N)$	-- nitrate-nitrogen
Na	-- sodium
F	-- fluoride
Se	-- selenium

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Mr. William D. Darby, Charlotte Harbor Water Association, was responsible for project management, and Martin R. Huxstep conducted the pilot plant tests. Dr. Alexander Padva, Environmental Quality Laboratory, Port Charlotte, Florida, was responsible for the EQL chemical analysis tests and provided consultation on all laboratory analyses and quality control efforts.

Special acknowledgment is given to Vincent B. Pickett, of Pickett, Duncan and Associates, Inc., Bartow, Florida, for providing the engineering services for system design and specifications, and to Ben Mohlenhoff, of Basic Technologies, Inc., Rivera Beach, Florida, for the installation of the systems.

Dr. Alexander Padva is also acknowledged for his assistance in providing review comments.

SECTION 1

INTRODUCTION

Reverse osmosis (RO) is a relatively new water treatment process; it has been applied successfully for desalting brackish water for domestic use for less than two decades. RO systems typically operate at 800 psig for treating sea water (35,000 mg/L total dissolved solids [TDS]) and at 400 psig for treating brackish waters in the 1,000 to 15,000 mg/L TDS range. Such systems are easily capable of producing water with a TDS concentration of 500 mg/L or lower.

During the 1970's, tremendous progress was made in membrane technology. Advancements not only occurred with the traditional 400 psig, 90-percent rejecting membranes, but even more significantly, with the reduced-pressure membranes that operate around 200 psig. Initially, the low-pressure membranes such as those used in this research project were capable of achieving only 40 to 50 percent rejection efficiency. Within the past several years, however, low-pressure membranes have been developed to achieve 80 to 90 percent rejection. The major advantages of these low-pressure membranes are lower energy requirements and subsequently lower operating costs.

Reverse osmosis is effective for the removal of most dissolved solids; specific removal in most cases depends on the weight, size, and valence of the ionic specie. Extensive studies have been conducted on the effectiveness of RO to reject the common water constituents, such as sodium, chloride, sulfate, TDS, calcium, and so forth. Very limited investigations have been conducted to evaluate the effectiveness of RO for removing many of the heavy metals and other inorganic contaminants listed in the National Interim Primary Drinking Water Regulations (NIPDWR).[1] The investigations have generally consisted of laboratory studies, and most results have not been verified on either a pilot-plant or full-scale level.[2-5]

The original objective of this research project was to determine the rejection efficiences of high- (400 psig) and low- (200 psig) pressure reverse osmosis systems for the removal of all the inorganic contaminants listed in the NIPDWR. Because of various problems as described within this report, some of the contaminants could not be investigated, however.

This progress report describes the reverse osmosis test systems, experimental procedures, and results of the initial tests on fluoride, nitrate, and arsenic. Subsequent reports will be issued periodically as the research project continues.

SECTION 2

CONCLUSIONS

1. Although several operational problems occurred, the two reverse osmosis systems performed effectively during the test period reported here.

2. As expected, the high-pressure system out-performed the low-pressure system significantly. Removal of the natural constituents and the spiked contaminants by each system varied with the substance measured. The order of rejection efficiency of the specific constituents measured was the same for each system, however.

3. The low-pressure system had a very wide range of rejection values compared with the high-pressure system. Considering the natural constituents monitored, the low-pressure system achieved the highest rejection on sulfate (85 percent) and its lowest on sodium (40 percent). The high-pressure system also achieved its best results on sulfate (99 percent) and its least results on sodium (90 percent).

4. The percent removal data suggest that rejection of the four spiked contaminants was independent of the feed water concentration. The order of removal of the contaminants from best to least for the high-pressure system was: arsenic V (97 percent), fluoride (92 percent), nitrate (78 percent), and arsenic III (65 percent). Removals by the low-pressure system were lower, but in almost the same order: arsenic V (79 percent), fluoride (60 percent), arsenic III (25 percent), and nitrate (20 percent).

5. Because of its low rejection capability, the low-pressure system was able to achieve the EPA MCL's when the feed water concentrations were only slightly above the MCL. The low-pressure system was particularly ineffective for arsenic III and nitrate removal.

6. The energy usage of the low-pressure reverse osmosis system was about half that required by the high-pressure system. Because of the low rejection efficiency of the low-pressure system, however, the cost savings might not be sufficient to offset the difference in efficiency of the high-pressure system. Furthermore, the high rejection efficiency of the high-pressure system could provide the opportunity for blending, whereas the low-pressure system would not.

SECTION 3

REVERSE OSMOSIS PILOT PLANT SYSTEMS

SYSTEM COMPONENTS

The pilot plant reverse osmosis system was housed in the Charlotte Harbor Water Association water treatment plant facilities in Harbour Heights, Florida. The system was typical of most reverse osmosis plants and consisted of source water from wells 123 m [400 ft] deep, pretreatment, two reverse osmosis systems, post treatment, and a disposal pond for the spent test waters. The equipment occupied an area of about 28.8 m^2 (320 ft^2).

The general engineering was provided by Picket, Duncan, and Associates, Inc., Bartow, Florida. The reverse osmosis systems, including the pretreatment equipment, all interconnecting piping and valves, and all monitoring instrumentation was supplied and installed as a predesigned and partially preconstructed package by Basic Technologies, Inc., Riviera Beach, Florida.

REVERSE OSMOSIS UNITS

The major components of the pilot plant facilities consisted of two separate reverse osmosis systems: (1) a conventional high pressure system (400 psig) and (2) a less conventional low-pressure system (180 psig). Each was originally designed to produce 1.97 L/S (31.3 gpm) of treated product water and 0.66 L/S (10.4 gpm) of reject water (75 percent recovery). The two parallel systems were designed to operate simultaneously; the total raw water requirement was therefore 5.26 L/S (83.3 gpm).

During the third month of the testing program, an irreversible fouling problem occurred following several weeks of nitrate testing. Because the problem could not be corrected, the membrane elements were replaced, and for economic reasons, the capacity of each system was reduced to 1.3 L/S (20.8 gpm) for the high-pressure system and to 0.98 L/S (15.6 gpm) for the low-pressure system.

The high-pressure reverse osmosis system, (hereinafter referred to as the RO system) was designed as a two stage system with 18 fiberglass reinforced plastic, 0.1-m-(4-in.) diameter by 2.3-m-(90-in.) long, permeator shells. Each shell contained 3 ROGA 4160 HR spiral-wound cellulose acetate membrane elements. The two-stage system was designed for 75 percent recovery having 12 first stage and 6 second stage permeators arranged in a 6-6-3-3 array (Fig. 1). The modified reduced flow system was achieved by reducing the total

number of permeators to 12 and rearranging the two stage system in a 4-4-2-2 array (Fig. 1).

The low pressure system, hereinafter referred to as the MB (membrane barrier) system, was originally designed as a two stage, 75-percent recovery system. The MB system contained 12 fiberglass-reinforced plastic, 0.1-m-(4-in.) diameter by 2.3-m-(90-in.) long permeator shells. Each shell contained 3 ROGA 4160 LP spiral wound, cellulose acetate elements. The configuration of the original system was eight permeators in the first stage and four permeators in the second stage structured in a 4-4-2-2 array (Fig. 1). The modified low-flow system had only six permeators and were arranged in a 2-2-1-1 array. Photographs of some of the RO system components are sho in Figures 1 a and 1 b.

TEST WATER

Two sources of test waters were orginally available: (1) two deep wells, 93 m (306 ft) and 139 m (457 ft), and (2) two shallow wells 9.1 m (30 ft). The two deep wells, which draw water from the upper Hawthorn Aquifer, supply the CHWA treatment plant and are located approximately 1.5 miles north-east of the facilities. During the initial testing program of October 1978 to March 1979, the deep-well test water consisted of a blend of the two wells. An analysis of a water sample from each deep well collected on November 16, 1977, is given in Table 1. Also shown in this table is an average of all source water samples collected during the experimental program.

TABLE 1. Chemical Analysis of Source Water

Constituent, mg/L (except as noted)	Well No. 1 (11/16/77)	Well No. 2 (10/8/77)	Source Water Blend of Well 1 & 2, Avg of 9 to 27 Samples
pH (units)	7.5	7.4	7.5
TDS	1156	1378	1104
Hardness (as $CaCO_3$)	460	490	428
Alkalinity (as $CaCO_3$)	108	106	109
Sulfate	152	210	105
Chloride	460	510	467
Calcium	76	96	82
Magnesium	66	60	54
Fluoride	1.3	1.2	--
Carbon Dioxide	7	8	8
Color (units)	< 5	5	3.2

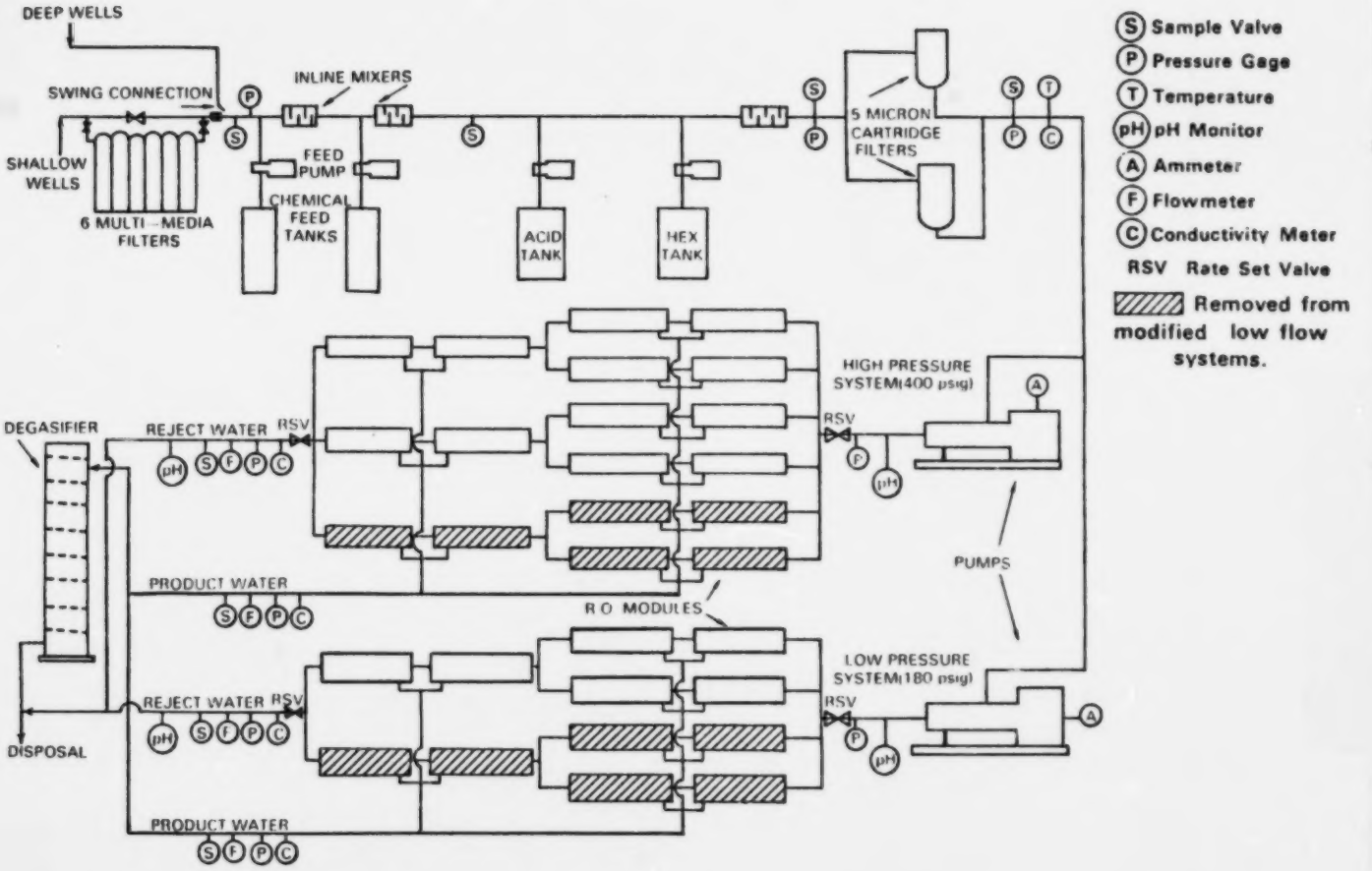
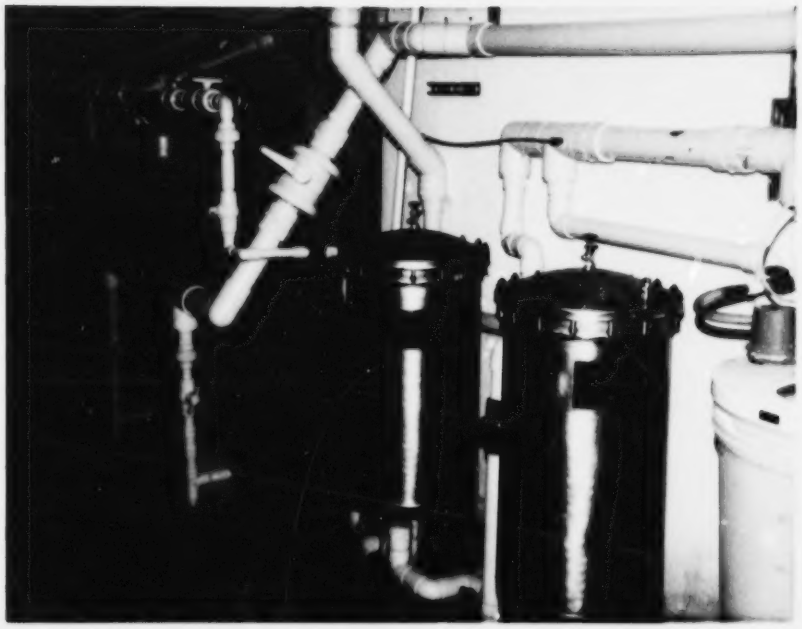


FIGURE 1. Flow Diagram of CHWA Reverse Osmosis Research Pilot Plant.



Pretreatment Components

Multi-media Filters

and

Cartridge Filters

Reverse Osmosis Elements

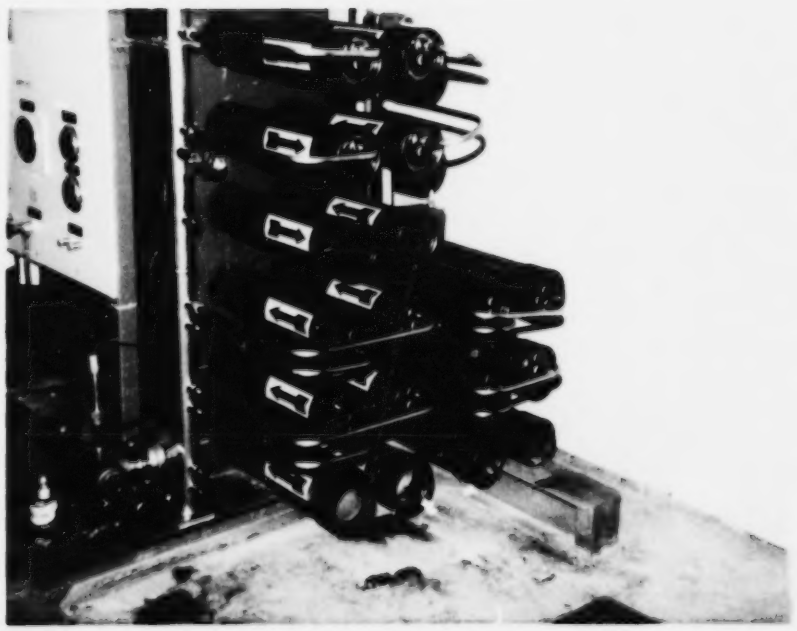
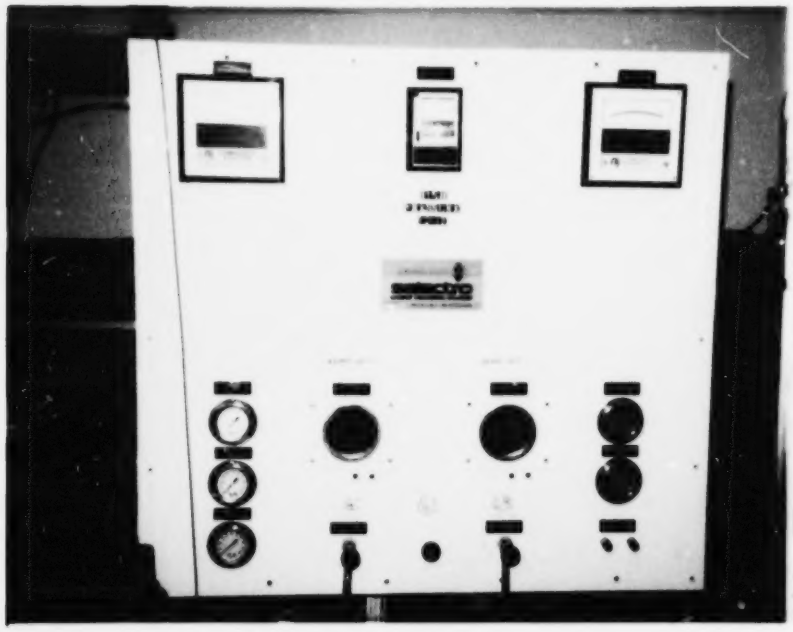


Figure 1a. Reverse Osmosis System Components



Individual System Monitoring Panel

Central Monitoring Panel

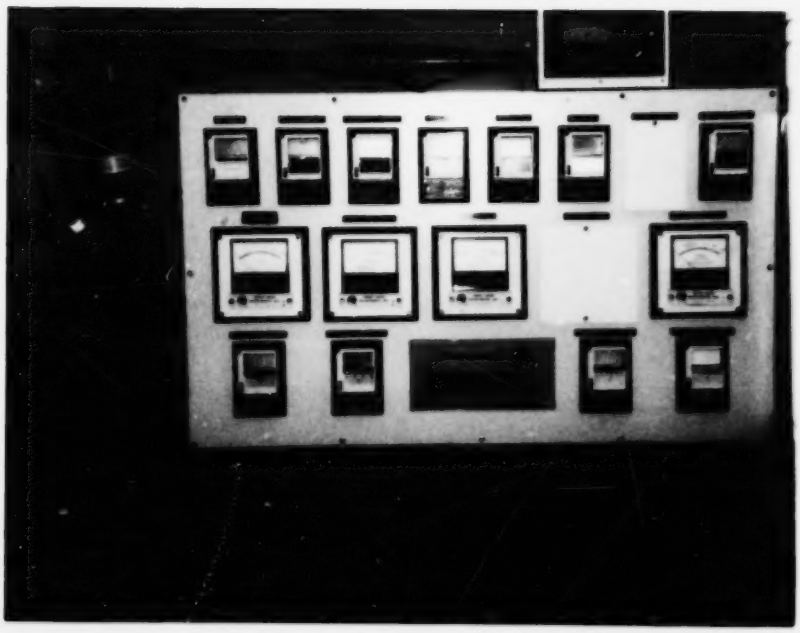


Figure 1 b. Reverse Osmosis System Components

The two shallow wells, dug specifically for this research project, are located adjacent to the treatment plant. The shallow well water was significantly different in quality to the deep well water; specifically, it had a lower total dissolved solids (TDS) concentration but was higher in color. During May, 1979, the acid storage tank of the CHWA facility burst allowing a large quantity of acid to enter the shallow groundwater and thereby altering its characteristics significantly. A new shallow groundwater source is therefore being sought.

PRETREATMENT AND POST TREATMENT EQUIPMENT

The pretreatment capabilities provided were granular multi-media filtration (Fig. 1 a), pH adjustment, hexametaphosphate addition, and cartridge filtration (Fig 1 b). Six granular multi-media filters were installed to treat only the shallow groundwater that was expected to pose problems to the RO membranes because of the high organic content. The other three pretreatment steps are common to most reverse osmosis systems to prevent calcium carbonate precipitation (pH adjustment), calcium sulfate precipitation (calcium sequestration with hexametaphosphate) and particulate fouling (5 micron cartridge filtration).

The two chemical feed systems for acid and hexametaphosphate injection consisted of an AMF Precision feed pump, a 189 L (50 gal) polyethylene tank, a liquid level switch, and suction and discharge piping. These systems were designed on estimated feed requirements of 80 mg/L of sulfuric acid and 10 mg/L of hexametaphosphate. An inline mixer was also installed down stream from the injection points to provide adequate mixing.

Cartridge filtration consisted of two parallel units each having a maximum flow capacity of 9.5 L/S (150 gpm). Each unit originally housed 42, 0.6 m by 3 m (2 in x 10 in), disposable, 5 micron, Harmsco filter cartridges. The units were also capable of housing the longer, 8.9 m (29.3 in), cartridges which were used after the first set was disposed of.

Post-treatment consisted of only a degasifier for the removal of hydrogen sulfide from the product water. The degasifier was a forced draft type, 4.5 m (15 ft.) by 0.6 m (2 ft.) and sized to handle at least 4.4 L/S (69.49 pm). Chlorination, although originally considered, was not provided because all of the test water, product and reject, was disposed of in two one-half acre ponds.

CONTAMINANT FEED SYSTEM

Two contaminant feed systems were provided and installed upstream from the acid chemical injection station. These two systems were similar to the chemical feed system. Each system consisted of an AMF Precision feed pump, a 189 L (50 gal) polyethylene tank, liquid level switch, and suction and discharge piping. The chemical feed pumps were variable speed type with stroke adjustment and an output range of 0.5 to 1 mL/S (0.5 to 1 gph). An inline mixer was also inserted after each injection point to improve mixing conditions.

MONITORING INSTRUMENTATION

Monitoring instrumentation was located on three separate panels, one on each reverse osmosis unit and one centralized panel located between the two systems (Fig 1 b). Each individual system panel contained the monitors and guages provided with standard commerical systems: four monitors for feed pH, product conductivity, product flow, reject flow; a recorder for feed pH; and five pressure gages for feed, reject, and product water, cartridge filter influent, and cartridge filter effluent.

The central panel was constructed for the research project to provide additional operational data. The instrumentation included five direct readout monitors and twelve recorders. The monitors were added for feed conductivity and for reject pH and conductivity for each unit. The twelve recorders were used to chart power usage (amperage), feed water pressure, and reject water pH, conductivity and pressure for each system and for the temperature and conductivity of the feed water before the split to enter each system.

SAMPLING PORTS

Because of the uncertainty of sample collection, fifteen sampling ports were installed along the treatment system. Although samples were expected to be limited to raw, reject, and product waters, the additional sampling ports were provided for flexibility in collecting chemical data from other parts of the pilot plant system. The locations of the sampling ports are shown in Fig. 1.

SECTION 4

PILOT PLANT EXPERIMENTS AND DATA COLLECTION

SYSTEM OPERATION

The test program was initiated October 23, 1978 after 64 hours and 79 hours of operation of the RO and MB systems respectively for system tuning and the collection of baseline operational data. Although the two pilot plant systems were designed to produce 1.97 L/S (31.3 gpm) each, the production flow flow was reduced to 1.75 L/S (27.8 gpm) each because of an increase in demand for raw water by the main CHWA production plant. The drop in production flow was accomplished by lowering the feed pressure for the RO and MB systems. At the lower flow rate, the RO feed pressure was 270 psig instead of the design pressure of 330 psig and the MB feed pressure was 160 instead of the design pressure of 180 psig.

After several weeks of testing, the pilot plant system was readjusted to increase the feed pressure to the original design rates. A Jordan valve, originally installed to control pressure variations that might occur by operating the pilot system simultaneously with the full scale plant, was removed. Concurrently, two malfunctioning solenoid valves were disassembled and interior components discarded. As a result of these adjustments, the product water flow rate was raised to 1.97 L/S (31.3 gpm) for each system and the feed pressures were increased to 330 psig for the RO system and 180 psig for the MB system.

The test program was conducted during the normal work week (Monday through Friday) with both systems running simultaneously for 7-8 hours per day using a single source of raw water spiked with a specific contaminant. All required premixing of contaminant solution and cleaning of injection tanks was performed on the weekends. Additionally, the systems were frequently operated on weekends with unspiked water to flush out any spiked contaminants in preparation for a new test run during the following week.

SYSTEM PERFORMANCE DATA

The operation of each pilot system was monitored with direct readout instrumentation on the central control panel and the individual panel on each system. System performance information was recorded twice daily; morning and afternoon. The morning readings were generally taken concurrently with the collection of water samples at 10 am and the afternoon readings on a rotating basis at 2, 3, or 4 pm.

Operational data collected consisted of pressure, pH, and conductivity of the feed, raw and reject water of each pilot plant system; pressure readings were recorded on the inlet and outlet side of the cartridge filter; electrical current (amperage) usage for the two high pressure pumps; water flow (product and reject); and hours of operation. A list of the data recorded is shown in Appendix A.

WATER SAMPLE COLLECTION

Test water samples were collected twice daily; in the morning at a fixed time, 10 am (about one hour after start up), and in the afternoon at varying times between 1:30 and 3:30 pm.

During the first week of testing, water samples were collected at each of the 10 sampling ports that included some redundancy, in order to determine the most suitable stations to sample. A review of these data indicated the need for only six samples: raw water, spiked feed water, and the product and reject waters from each system.

The amount of water sample collected varied according to the analyses to be performed and the collection container varied according to the analysis. Water samples collected for routine on-site analyses, such as hardness and alkalinity, were collected in 1-liter polyethylene bottles. Samples for analyses by the Environmental Quality Laboratory were collected in wide mouth 250 and 500 mL polyethylene bottles provided by the Laboratory. These samples were preserved according to the procedures recommended by the USEPA[6].

CHEMICAL ANALYSIS

The water samples collected twice daily were analyzed partially on-site and partially by the Environmental Quality Laboratory (EQL), Port Charlotte, Florida. The routine in-house analyses were conducted immediately following sample collection and consisted of pH, total dissolved solids (TDS), total alkalinity, total hardness, calcium, magnesium and chloride. The analytical methods used are listed in Table 2.

Analyses of the spiked chemicals, such as fluoride, nitrate, arsenic, and selenium, were conducted by the EQL. Twice a week, usually Tuesday and Thursday, EQL also analyzed water samples for color, sulfate, chloride, sodium, TDS, total organic carbon, total hardness, alkalinity, calcium, and magnesium by methods listed in Table 2. The last four listed tests were conducted to support the more frequent on-site analyses.

TABLE 2. List of Chemical Analyses and Analytical Methods

Laboratory*	Parameter	Frequency	Analytical Method
CHWA (on-site)	pH	twice/day	Corning pH meter 125
CHWA	TDS	twice/day	Myron L TDS meter (conductivity)
CHWA	Alkalinty	twice/day	Colorimetric titration
CHWA	Hardness	twice/day	Titrimetric, EDTA
CHWA	Calcium	twice/day	Titrimetric, EDTA
CHWA	Magnesium	twice/day	Calculation
CHWA	Chloride	twice/day	Argentometric
EQL	Color	twice/week	Colorimetric, Pt-Co
EQL	Sulfate	twice/week	Turbidimetric
EQL	Chloride	twice/week	Argentometric
EQL	Sodium	twice/week	Flame Photometric
EQL	TDS	twice/week	Gravimetric, dried at 180°C
EQL	TOC	twice/week	Combustion or Oxidation
EQL	Hardness	twice/week	Titrimetric, EDTA
EQL	Alkalinity	twice/week	Titrimetric (pH 4.5)
EQL	Calcium	twice/week	Titrimetric, EDTA
EQL	Magnesium	twice/week	Calculation
EQL	Fluoride	twice/day	Potentiometric, ion selective electrode
EQL	Nitrate	twice/day	Colorimetric, automated Cd reduction
EQL	Arsenic	twice/day	AA, graphite furnace
EQL	Selenium	twice/day	AA, graphite furnace

* CHWA - Laboratory on-site at the Charlotte Harbor Water Association Reverse Osmosis treatment plant

EQL - Environmental Quality Laboratory, Port Charlotte, Florida

QUALITY CONTROL

Quality control was considered to be essential to the data collection activities. Specific quality control plans were established for both the operational measurements and the chemical analyses of the water samples.

Water samples were collected daily and analyzed on-site for TDS, alkalinity, pH, hardness, calcium, magnesium and chloride. For quality control reasons, duplicate samples were collected twice a week for analysis by the Environmental Quality Laboratory, a state certified laboratory. The analytical methods utilized by each lab are listed in Table 2 and in some cases different methods were used. Standard laboratory quality control

procedures were utilized; quality control standard solutions were analyzed daily to verify the accuracy of the method. Where duplicate samples were analyzed by each lab, both results are reported for comparison.

At least ten percent of the samples were analyzed in duplicates to establish and maintain method precision while unknown quality performance samples were provided only once during the study phase for fluoride, nitrate and arsenic, and TOC. The results of these analyses were within the accepted limits established by the Environmental Monitoring and Support Laboratory (EMSL) US EPA. Split raw water samples for total organic carbon (TOC) were analyzed by EQL and by the Drinking Water Research Laboratory, (DWRD) USEPA, Cincinnati and the results were significantly different. Investigations into the reasons for these differences were made but not resolved at the time of this report's preparation. The results of the TOC analyses by EQL are presented in this report, however.

SCHEDULE

Initial plans were to conduct removal tests for eight of the 10 inorganic contaminants in the NIPDWR in the following order: fluoride, nitrate, arsenic, selenium, lead, cadmium, chromium, and mercury. Silver and barium were dropped from the program because silver is not a common drinking water problem and barium would precipitate out of the high sulfate water. Because of strict disposal regulations for mercury, testing of this element was to be very limited or eliminated depending on the disposal method available.

The first test run with a spiked contaminant, fluoride, began Oct. 23, 1978. Test runs were planned for 2, 3 or 5 days at the same initial feed water concentration; the high concentration tests lasting only 2 or 3 days in contrast to the longer 5 day low concentration test runs.

The schedule for the test runs by days of operation is given in Table 3. The test program (62 days) took place between October 23, 1978 and March 16, 1980. Between December 6, 1978 and January 30, 1979, no tests were conducted because of a membrane fouling problem that eventually led to the replacement of the membranes. Several tests were also attempted for cadmium and lead removal, but neither contaminant could be detected in the spiked or treated water. Several laboratory experiments with the test water suggested that hydrogen sulfide was reacting with both metals forming a sulfide precipitate that was probably filtered out by the cartridge filters.

Several weeks of tests were scheduled for selenium removal. Analytical results of the test samples indicated unrealistic concentrations in numerous water samples and in some samples, selenium was not detected. Consequently, the results of these tests are not reported. These tests will be repeated in Phase II when the analytical problems are solved.

TABLE 3. Schedule of Testing Program

Days of Operation	Contaminant	Average Contaminant Concentration in Feed Water mg/L
1 - 5	F	4.72
6	F	7.06
7 - 8	F	8.84
9 - 10	F	12.56
11 - 15	NO_3 - N	15.1
16 - 18	NO_3 - N	17.4
19	NO_3 - N	33.5
20	NO_3 - N	15.9
21	NO_3 - N	34.6
22 - 23	NO_3 - N	22.2
24 - 25	NO_3 - N	41.4
26	As III	1.55
27	As III	0.39
29 - 30	As III	0.64
32 - 35	As III	2.59
36	As III	0.76
37 - 45	Se IV	-
47 - 48	As V	0.54
50	As V	1.0
51	As V	5.31
52 - 61	Se VI	-

SECTION 5

RESULTS

SYSTEMS PERFORMANCE

The most common parameters used to evaluate RO performance are system pressures, flows, and water quality (conductivity). As outlined in previous sections, monitoring instrumentation provided continuous readouts of feed, product, and reject pressures (psig); product and reject flow (gpm); and feed, product, and reject conductivity (micromhos). These data were recorded twice daily along with other operating information on a record sheet shown in Appendix A.

Because of several different problems, the two pilot plant systems were not always operated at design flows and pressures during the entire testing period of October 23, 1978 to March 3, 1979. During the first 19 days of operation, the two systems were operated at less than design capacity because of a lack of feed water. The average system feed pressures were 265 psig (RO) and 163 psig (MB) and average product flows were 1.75 L/S (27.8 gpm) (RO) and 1.74 L/S (27.6 gpm) (MB). The average percents of salt rejection determined by conductivity readings were 95.2 percent for the RO system and 53.9 percent for the MB system.

System pressures and flows were increased on day 20 by removing a Jordan pressure reducing valve and two malfunctioning solenoid valves in the main feed water lines. These modifications resulted in a feed water pressure gain and a subsequent product water flow increase. During days 20-27, feed pressures averaged 339 psig (RO) and 184 psig (MB). Product water flows were about equal at 1.98 L/S (31.4 gpm) for the RO system and 1.96 L/S (31.1 gpm) for the MB system. Although pressures increased, the average percent rejection decreased slightly to 94.4 percent (RO) and 44.6 percent (MB).

During the days following the pressure and flow increase (nitrate testing), a slow but steady increase in the pressure differential between feed water and reject water was observed to the point where any further increase was considered cause for shut down and investigation. Upon the advice of Basic Technologies, the study program proceeded cautiously with Arsenic III tests. After three days, the differential pressure rose and a yellow-brown substance was found in the reject water samples. At this point, the study was immediately halted and an investigation conducted into the cause of the problem.

The investigation revealed a serious fouling problem that could not be easily solved. Various cleaning procedures were tried (described in Appendix

B) but all failed and a decision was made to replace the membranes with new ones. Because of budget limitation, the capacity of the two systems was reduced as mentioned in Section 1. During the third test period that followed, the feed pressures averaged 359 psig (RO) and 187 psig (MB). Flows were reduced because of fewer membrane elements to 1.3 L/S (20.6 gpm) for the RO system and to 0.98 L/S (5.6 gpm) for the MB system. Salt rejection was about the same; 93 percent rejection for the RO system and 43.9 percent for the MB system.

A summary of performance for the three test periods is given in Table 4. This information is also graphically shown in Figures 2 through 5. The power requirement for each system is also summarized in Table 4; the power usage for the MB system (9.6 - 11.3 amps) was about half of that required for the RO system (20.8 - 22.5 amps). An evaluation of the monitoring equipment in December, 1979 suggested that pressure and flow readings might have been low. For this report, however, the values are reported as recorded.

Analysis of the feed water showed that pH adjusted to 6.5 or lower and the addition of sodium hexametaphosphate was required to prevent calcium carbonate and calcium sulfate precipitation respectively. The pH of the feed water was, therefore, adjusted with sulfuric acid to between 5.0 and 6.0. The pH of feed, product, and reject water was monitored and the results are shown in Figure 6.

Sodium hexametaphosphate was added to the feed water to achieve a concentration of 5 to 7 mg/L.

REMOVAL OF NATURAL CONSTITUENTS

Reverse osmosis systems and membranes are commonly rated on their ability for salt rejection or salt passage, i.e., the average percent of total dissolved solids that is either removed or passed through the system. Typically, a 400 psig RO system will reject 90 - 95 percent of the TDS (5 - 10 percent salt passage).

During the contaminant removal testing period, several common ground water constituents were routinely measured for removal by the RO and MB systems: TDS, hardness, calcium, magnesium, sulfate, chloride, sodium, color, carbon dioxide, and total organic carbon (TOC). As explained in Section 4, water samples were analyzed on-site by the CHWA and off-site by EQL depending on each laboratory's capability. The methods and procedures used are also described in Section 4. For comparison of split samples, a summary of the results from each laboratory is given in Table 5. The data is also broken down according to the three periods of different operating conditions.

A review of the test data shows a very significant difference between the performances of the two reverse osmosis systems. The TDS rejection by the RO system (94-95 percent) was approximately twice the rejection range for the MB system (45 - 52). The rejection range for specific substances was also significantly higher in the RO system although the difference was not always of the same magnitude. The percent rejection of the specific inorganic sub-

TABLE 4. Summary of RO and MB Performance Data

Item	Performance Data (Averages)											
	Day 1 to 19				Day 20 to 27				Day 28 to 69			
	10/23/78 to 11/16/78				11/31/78 to 12/07/78				1/29/79 to 3/28/79			
	Pressure psig	Flow L/S (gpm)	Conductivity* µmho	Power amps	Pressure psig	Flow L/S (gpm)	Conductivity µmho	Power amps	Pressure psig	Flow L/S (gpm)	Conductivity µmho	Power amps
RO SYSTEM												
Feed	265	2.30 (37.1)	1920	22.5	339	2.6 (41.8)	1862	24.1	359	1.73 (27.4)	1816	20.8
Product	13	1.76 (27.8)	104	-	8	1.99 (31.4)	105	-	6	1.30 (20.6)	127	-
Reject	232	0.59 (9.3)	5158	-	31	0.66 (10.4)	5562	-	319	0.43 (6.4)	5245	-
Percent Recovery	-	74.9	-	-	-	75.1	-	-	-	75.1	-	-
Percent Rejection	-	-	94.6	-	-	-	94.4	-	-	-	93.0	-
MB SYSTEM												
Feed	163	2.32 (36.9)	1920	11.3	184	2.62 (41.5)	1862	11.7	187	1.32 (20.9)	1815	9.6
Product	14	1.74 (27.6)	1005	-	7	1.96 (31.1)	1030	-	5	0.99 (15.7)	1019	-
Reject	120	0.59 (9.3)	4404	-	124	0.66 (10.4)	4634	-	135	0.33 (5.2)	4719	-
Percent Recovery	-	74.8	-	-	-	74.9	-	-	-	75.1	-	-
Percent Rejection	-	-	47.6	-		-	44.6	-	-	-	43.9	-

*Because of instrument problems, feed and reject conductivity values are based on only days 7 - 19.

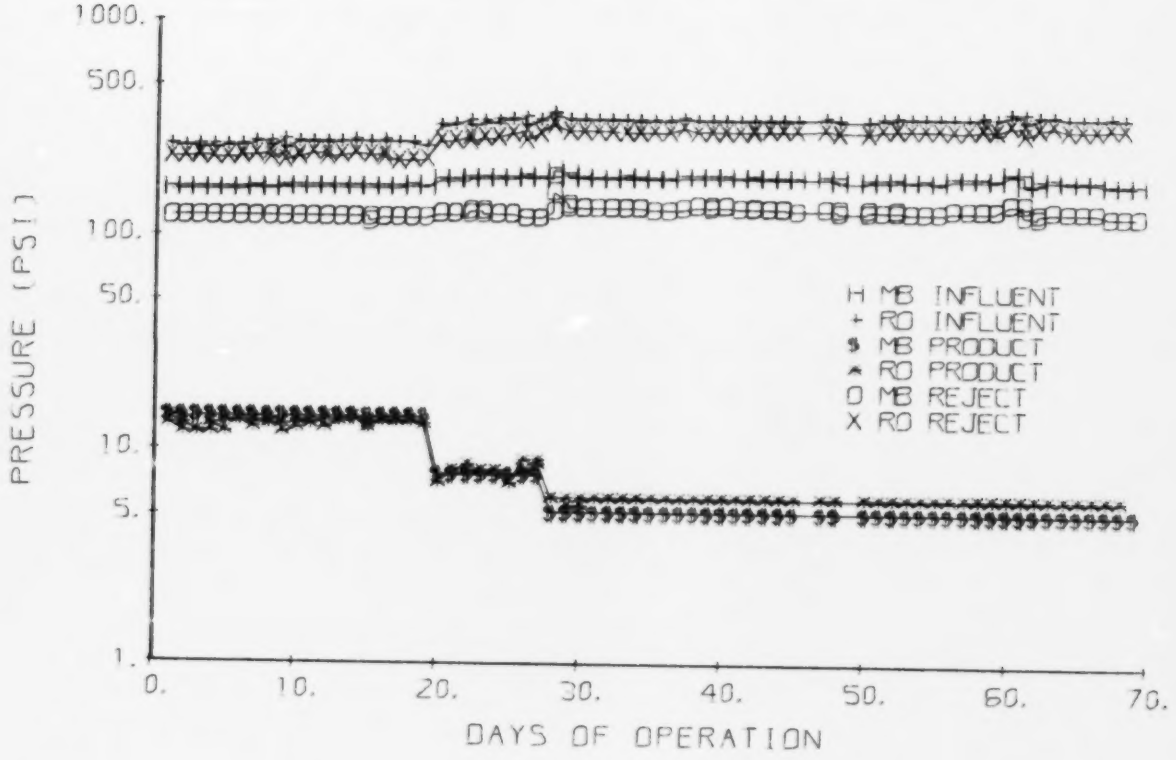


Figure 2. Operating Pressures of Systems During Test Runs

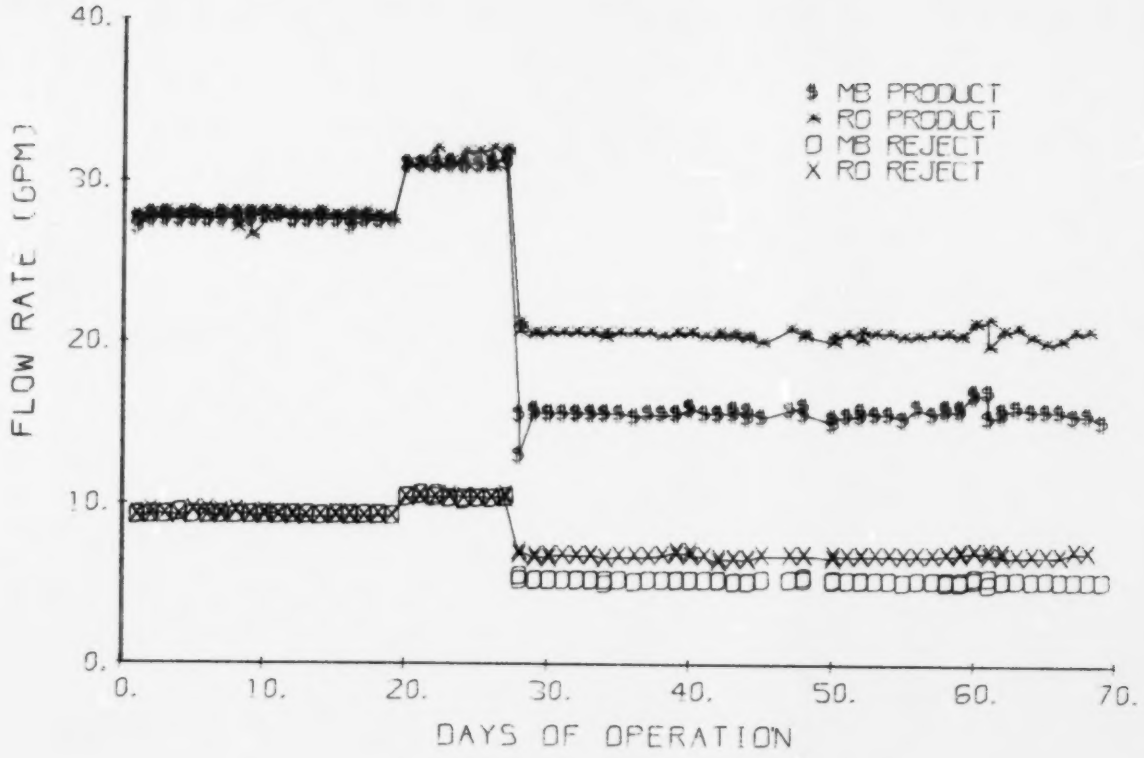


Figure 3. Flow Rates of Systems during Test Runs

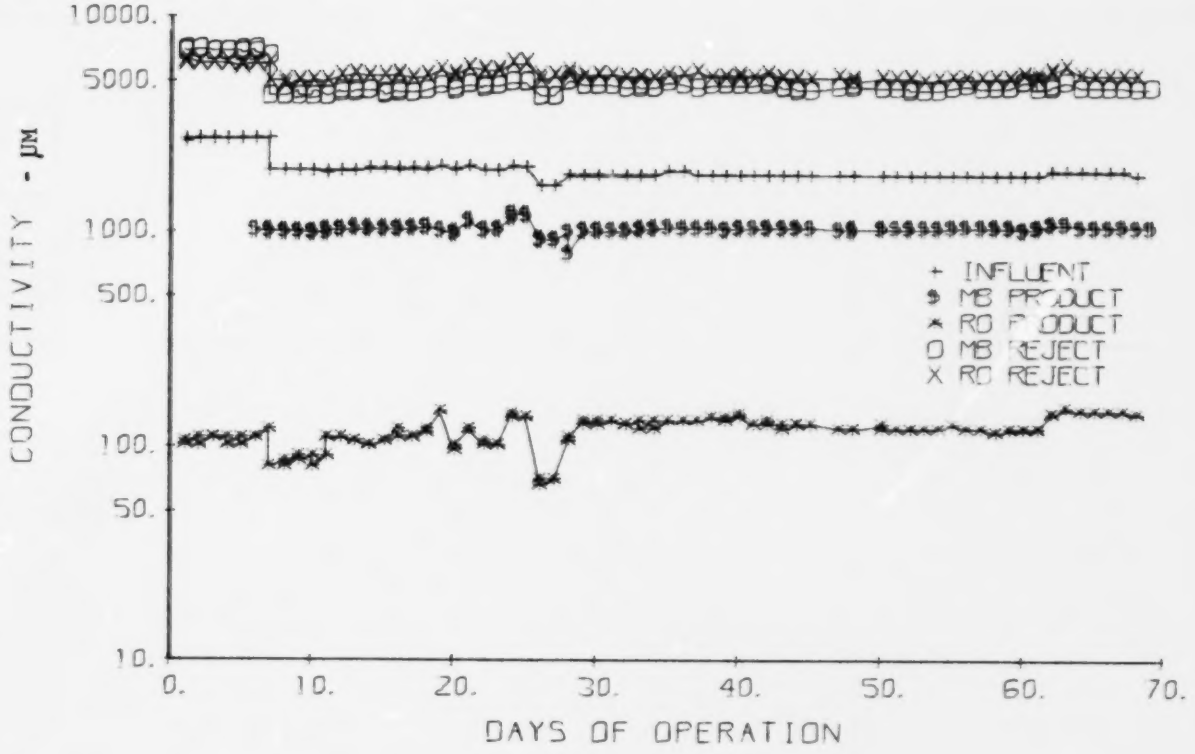


Figure 4. Conductivity of Feed, Product and Reject Waters During Test Runs

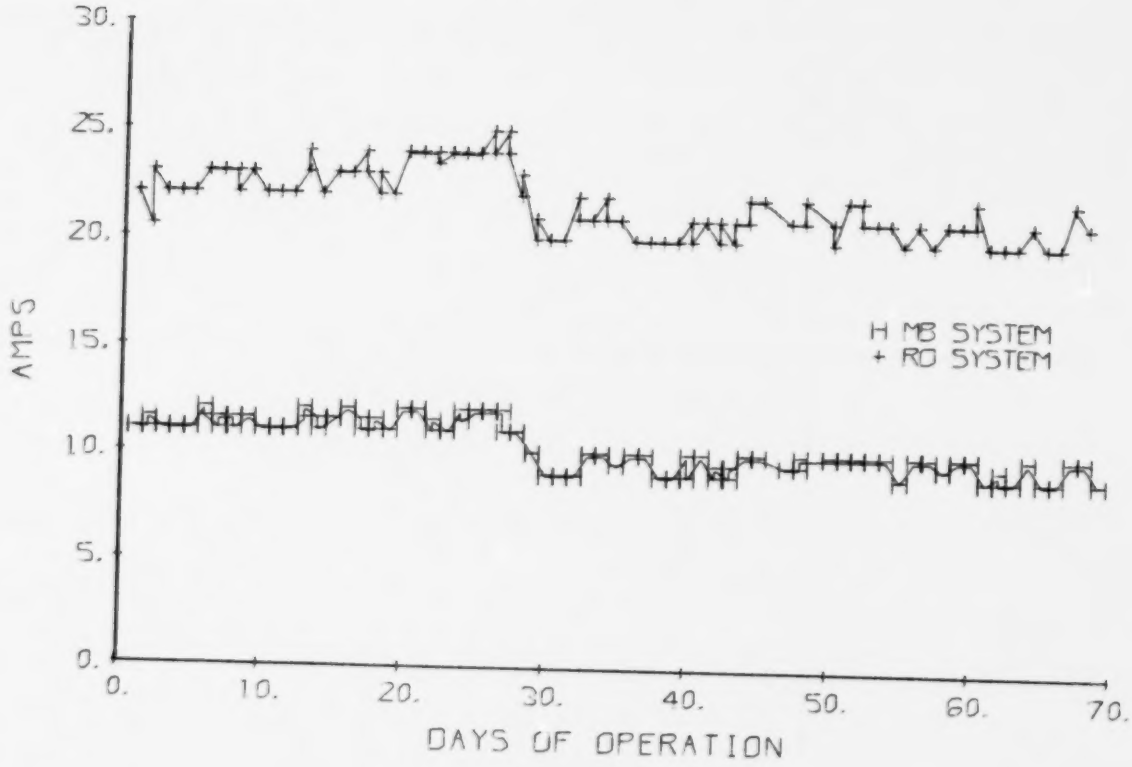


Figure 5. Power Usage of Systems during Test Runs

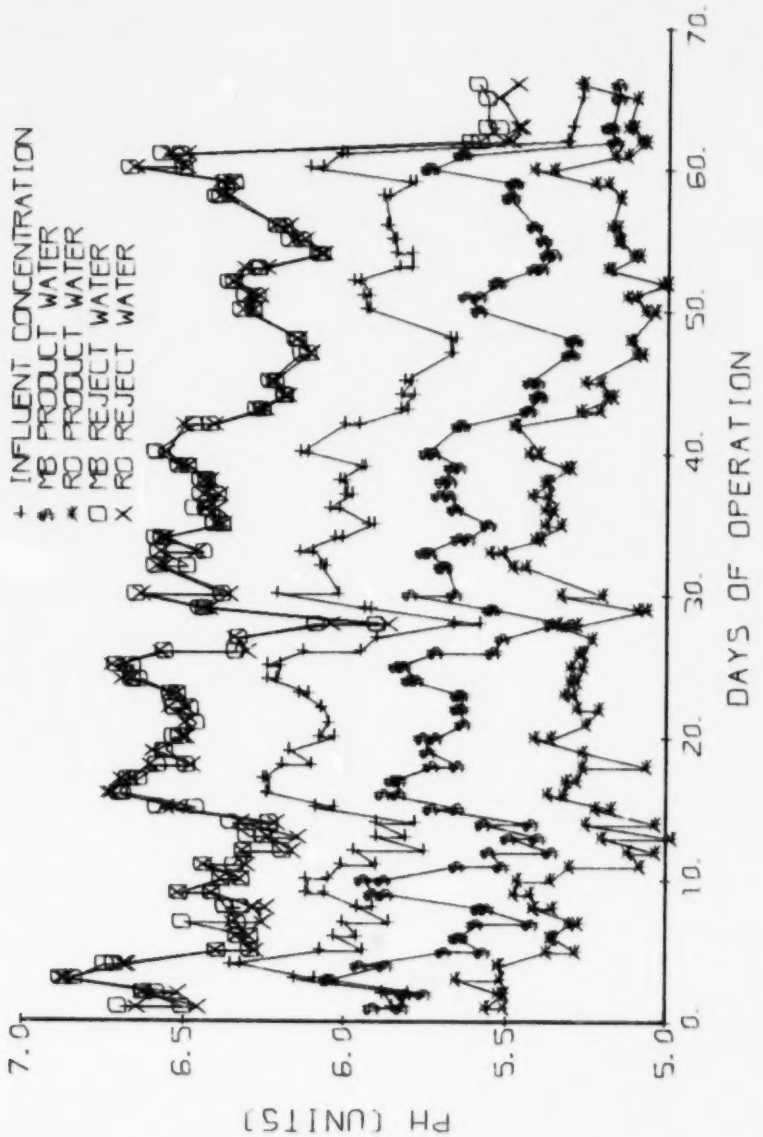


Figure 6. pH of Feed, Product and Reject Waters during Test Runs

Table 5. Summary of Chemical Analysis of Water Samples from Pilot Plant Systems*

Constituent (mg/L)	Influent Conc.	RO SYSTEM (265 psig) Product Conc.	RO SYSTEM (265 psig) Reject Conc.	RO SYSTEM (265 psig) Percent Rejection	MB SYSTEM (163 psig) Product Conc.	MB SYSTEM (163 psig) Reject Conc.	MB SYSTEM (163 psig) Percent Rejection
	Day 1 to 19						
TDS							
CHWA	1315	61	3951	95.4	683	3301	48.1
EQL	1175	61	3430	94.8	608	2711	48.3
HARDNESS**							
CHWA	414	8	1295	98.0	149	1253	63.9
EQL	430	14	1313	96.6	148	1333	65.5
CALCIUM**							
CHWA	220	5	660	97.9	78	640	64.3
EQL	180	3.8	565	97.9	65	572	63.7
MAGNESIUM**							
CHWA	195	4	635	98.2	71	614	63.4
EQL	248	10.7	746	95.7	82	758	66.9
CHLORIDE							
CHWA	562	50	1489	91.1	310	1237	44.8
EQL	463	30	1255	93.6	270	974	41.6
SULFATE							
EQL	158	1	403	99.1	22	530	85.8
SODIUM							
EQL	208	15.3	592	92.6	122	435	41.1
COLOR							
EQL	2	1.6	4.4	21.5	2	4.4	0
TOC							
EQL	12.3	9.5	24.8	22.8	11.6	21.6	5.7

*Average concentration of water samples during test period
**as $CaCO_3$

Table 5. Summary of Chemical Analysis of Water Samples From Pilot Plant Systems* (Continued)

Constituent (mg/L)	Influent Conc.	RO SYSTEM (339 psig) Product Conc.	RO SYSTEM (339 psig) Reject Conc.	RO SYSTEM (339 psig) Percent Rejection	MB SYSTEM (184 psig) Product Conc.	MB SYSTEM (184 psig) Reject Conc.	MB SYSTEM (184 psig) Percent Rejection
	Day 20 to 27						
TDS							
CHWA	1362	64	4216	95.3	679	3368	50.2
EQL	1214	66	3536	94.6	615	3014	49.3
HARDNESS**							
CHWA	410	9	1307	97.8	147	1253	64.3
EQL	423	11	1380	97.4	151	1325	64.2
CALCIUM**							
CHWA	229	6	686	97.6	81	648	64.6
EQL	190	8	620	96.3	68	585	64.4
MAGNESIUM**							
CHWA	181	4	620	98.0	66	603	63.6
EQL	234	4	762	98.2	86	738	63.5
CHLORIDE							
CHWA	574	51	1604	91.1	335	1227	41.6
EQL	452	20	1370	95.7	260	1064	42.3
SULFATE							
EQL	143	1	465	99.4	23	611	84.1
SODIUM							
EQL	201	16	665	92.1	128	493	36.1
COLOR							
EQL	28	7	3	75.4	25	6	12.7
TOC							
EQL	16	7	19	55.8	12	25	25.2

*Average concentration of water samples during test period
**as $CaCO_3$

Table 5. Summary of Chemical Analysis of Water Samples From Pilot Plant Systems* (Continued)

Constituent (mg/L)	Influent Conc.	RO SYSTEM (359 psig) Product Conc.	RO SYSTEM (359 psig) Reject Conc.	RO SYSTEM (359 psig) Percent Rejection	MB SYSTEM (187 psig) Product Conc.	MB SYSTEM (187 psig) Reject Conc.	MB SYSTEM (187 psig) Percent Rejection
		Day 28 to 69 Days					
TDS							
CHWA	1284	44	4038	96.5	616	3350	52.0
EQL	1160	83	3750	92.8	640	3285	44.8
HARDNESS**							
CHWA	426	10	1338	97.7	147	1397	65.4
EQL	419	13	1453	96.9	140	1481	66.5
CALCIUM**							
CHWA	234	6	688	97.4	81	716	65.5
EQL	210	8	745	96.3	68	688	67.3
MAGNESIUM**							
CHWA	198	4	637	97.9	67	674	66.1
EQL	213	4	763	97.3	70	791	66.2
CHLORIDE							
CHWA	524	68	1539	87.1	298	1265	43.1
EQL	473	33	1463	93.1	276	1144	41.6
SULFATE							
EQL	115	1	396	99.0	20	486	82.5
SODIUM							
EQL	173	21	576	87.7	96	439	44.4
COLOR							
EQL	9.6	3.7	13	61.5	6.5	13.4	32.3
TOC							
EQL	14	11	22	23.2	10	26	29.7

*Average concentration of water samples during test period
**as $CaCO_3$

stances varied, but the order, by removal percentage, was generally the same for both systems. For example, the percent rejection of the RO system for inorganics measured was sulfate (99), magnesium (97-98), calcium (96-97), sodium (88 - 93), and chloride (87 - 93). For the MB system, the order was about the same, sulfate (83 - 85), magnesium (63 - 66), calcium (63 - 65), chloride (42 - 45) and sodium (36 - 44). A very wide range occurred with the MB system where sulfate rejection was about 85 percent in comparison to around 44 percent for sodium and chloride.

Table 5 indicates only small differences in rejection values between the three periods of different operating conditions. Although it is not consistent for all measurements, the general trend was higher rejection at the higher operating pressures. Furthermore, where comparisons can be made, the removal percents by laboratory were very similar although the actual chemical measurements may have differed. These results suggest that the test methods were consistent within the laboratories even though the absolute values may have varied.

Color measurement, a very subjective test, was made by EQL. Table 5 shows a vast difference in the color of the influent water between the three test periods. These differences are attributed to the spike chemicals and not necessarily to the change in the source water quality.

Questions have been raised concerning the high amount of TOC in the source water. Split samples with the EPA Laboratory, Cincinnati, Ohio using different equipment have suggested much lower values of TOC in the 1 - 2 mg/L range, although quality assurance samples have given good results by both laboratories. The reason for the differences is not known at this time.

FLUORIDE REMOVAL

The first contaminant studied was fluoride whose MCL (1.4 to 2.4 mg/L) varies with the average daily temperature of a specific location. Tests were conducted for 10 days during which time the fluoride concentration of the source water was varied at four different levels ranging from 4.7 to 12.5 mg/L. The results of these tests are shown in Fig. 7 and are summarized in Table 6.

The test results show consistent rejection of fluoride by both systems throughout the influent concentration range. The RO system achieved removals of 90.3 to 93.4 percent and the low pressure MB system 58.3 to 62.4 percent. Because percent rejection was consistent, the product water concentrations of each system increased with influent concentration. The fluoride concentration of the RO product water was always less than 1 mg/L (0.31 to 0.94 mg/L) and the MB product water increased from 1.86 to 4.72 mg/L. as the influent concentration was elevated from 4.7 to 12/5 mg.L The high pressure RO system therefore was easily capable of achieving the MCL even at the high 12.5 mg/L concentration. The lower rejection MB system is practical only for source waters having a fluoride concentration in the lower range of 2 - 6.5 mg/L.

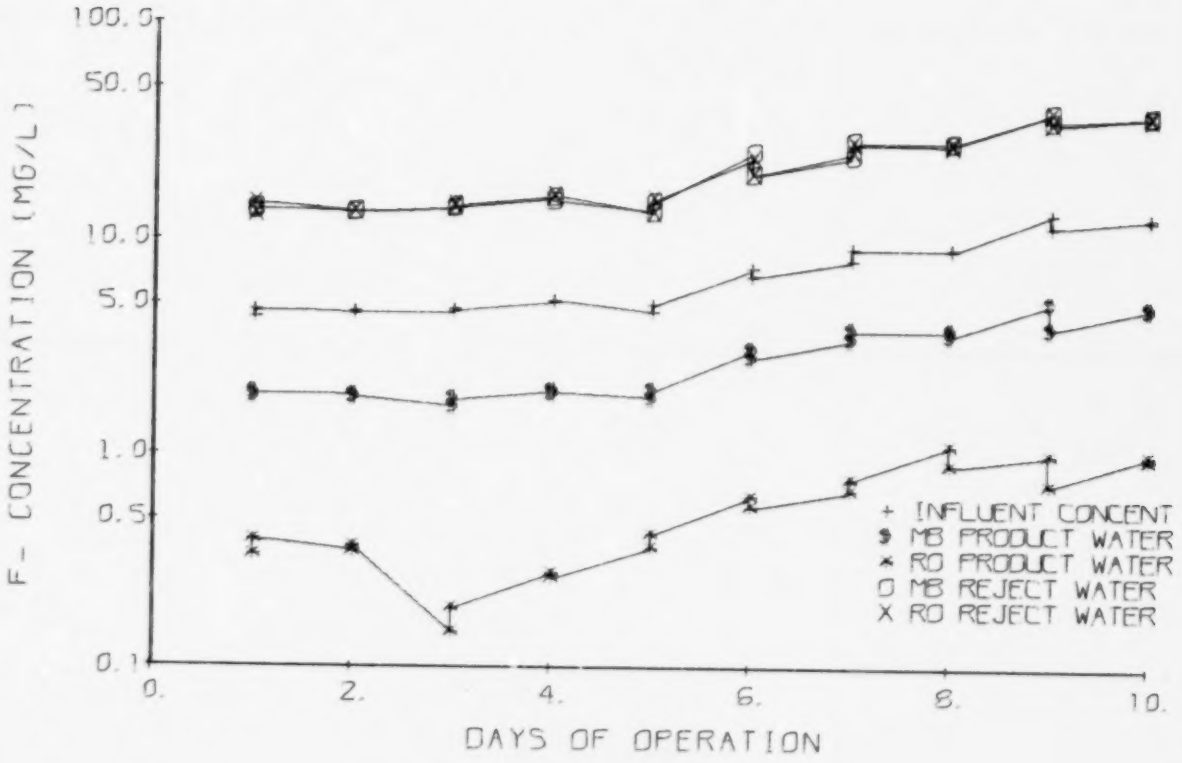


Figure 7. Fluoride Removal by Reverse Osmosis Systems

TABLE 6. Summary of Fluoride Removal Tests

Test Period Days of Operation	Source Water Concentration (mg/L)	RO SYSTEM			MB SYSTEM		
		Product (mg/L)	Reject (mg/L)	Percent Removal	Product (mg/L)	Reject (mg/L)	Percent Removal
1 - 5	4.72	0.31	14.08	93.4	1.86	13.99	60.6
6	7.06	0.60	21.85	91.5	2.97	22.55	57.9
7 - 8	8.84	0.86	27.10	90.3	3.69	27.38	58.3
9 - 10	12.56	0.94	37.36	92.5	4.72	37.88	62.4

NITRATE REMOVAL

RO is reported to be only moderately effective for nitrate removal.[7] Thirteen days of testing were completed for nitrate removal; the raw water NO_3-N concentration varied from 15 to 41 mg/L. The results of these tests (Table 7 and Figure 8), show RO system removals of 74 to 80 percent and MB system removals of 6 to 24 percent. Under the test conditions imposed, product water concentrations were below the 10 mg/L limit (3.5 to 8.9 mg/L) for the RO system and always above the MCL with the MB system (12 to 34 mg/L). Assuming rejection percentages of 75 percent for the RO system and 25 percent for the MB system, the MCL can be achieved only when the raw water concentration does not exceed 40 mg/L for the RO system and 13 mg/L for the MB system.

ARSENIC REMOVAL

Although arsenic can occur in aquatic systems in four oxidation states, it is normally found as an anion with acid characteristics in only the trivalent (arsenite) and pentavalent (arsenate) forms. Thus, tests were conducted for the removal of both valences, As III and As V, using sodium arsenite and sodium arsenate as the spike chemicals.

Sorg reports that arsenic III is generally more difficult to remove than arsenic V by most all treatment methods.[8] The principal reason suggested for the difference is that the predominant arsenic III specie is a neutral anion, H_3AsO_3. The predominant arsenic V forms are $H_2AsO_4^-$ and $HAsO_4^{-2}$.

Ten days of tests were conducted for the removal of arsenic III with arsenic III concentrations adjusted from 1.1 mg/L to 4.2 mg/L. Removals, summarized in Table 8 and Fig. 9, ranged from 63 to 73 percent with the RO system and 12 to 42 percent with the MB system. Neither system was capable of achieving the arsenic MCL when the source water arsenic concentration was in the test range of 1.1 - 4.2 mg/L. The product water concentrations were 0.39 to 1.55 with the RO system and 0.72 to 3.70 for the MB system. Assuming a rejection of 65 percent for the RO system and 30 percent for the MB system, the 0.05 mg/L MCL could be achieved only when the source water concentration did not exceed 0.14 mg/L and 0.07 mg/L respectively.

Four days of tests were conducted for arsenic V removal and the source water concentration was varied from 0.54 to 5.3 mg/L. The results of these tests (Table 8 and Fig. 10) show an average removal of about 94 percent with the RO system and about 79 percent for the MB system. Product water concentrations ranged from 0.05 to 0.08 mg/L for the RO system and 0.10 to 1.03 mg/L for MB system. Using the average reject percents for each system, the MCL can be achieved providing the raw water arsenic concentration does not exceed 0.83 mg/L for the RO system and 0.23 mg/L for the MB system. A comparison of arsenic III and V once again indicates that arsenic V is more effectively removed than arsenic III.

TABLE 7. Summary of Nitrate Removal Tests

Test Period Days of Operation	Average Source Water Conc. (mg/L) asN	RO System			MB System		
		Product Water Conc. mg/L asN	Reject Water Conc. mg/L asN	Percent Removal	Product Water Conc. mg/L asN	Reject Water Conc. mg/L asN	Percent Removal
11 - 15	15.1	3.5	39.5	76.8	11.4	22.5	24.5
16 - 18	17.4	4.5	43.2	74.1	14.5	28.3	16.7
19	33.5	8.2	85.9	75.7	31.5	37.3	6.0
20	15.9	3.2	40.8	79.7	12.1	23.9	24.0
21	34.6	6.9	85.5	80.0	27.1	56.7	21.7
23 - 24	22.2	5.0	58.8	77.6	19.4	36.4	12.9
24 - 25	41.4	8.9	109.6	78.6	33.7	66.8	18.6

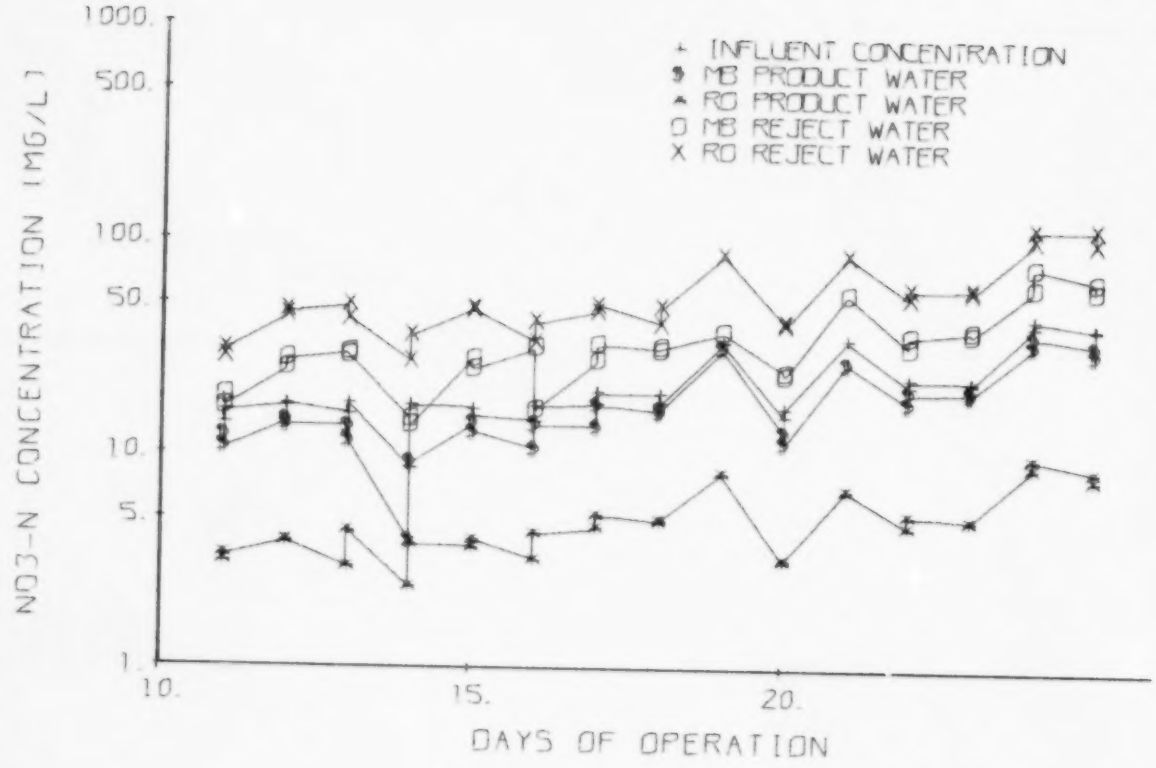


Figure 8. Nitrate Removal by Reverse Osmosis Systems

TABLE 8. Summary of Arsenic Removal Tests

Test Period Days of Operation	Source Water Concentration (mg/L)	RO SYSTEM			MB SYSTEM		
		Product (mg/L)	Reject (mg/L)	Percent Removal	Product (mg/L)	Reject (mg/L)	Percent Removal
26	AsIII - 4.20	1.55	13.6	63.1	3.70	9.75	11.9
27	AsIII - 1.14	0.39	3.4	65.8	0.72	3.25	36.8
29 - 30	AsIII - 2.12	0.64	5.5	69.8	1.40	5.13	34.0
32 - 35	AsIII - 2.59	0.92	7.2	64.4	1.50	4.26	42.1
36	AsIII - 2.80	0.76	7.0	72.9	1.81	6.46	35.4
47 - 48	AsV - 0.54	0.05	1.98	90.7	0.10	2.18	81.5
50	AsV - 1.0	0.05	3.44	95.0	0.23	3.66	77.0
51	AsV - 5.31	0.08	17.4	98.5	1.03	18.8	80.6

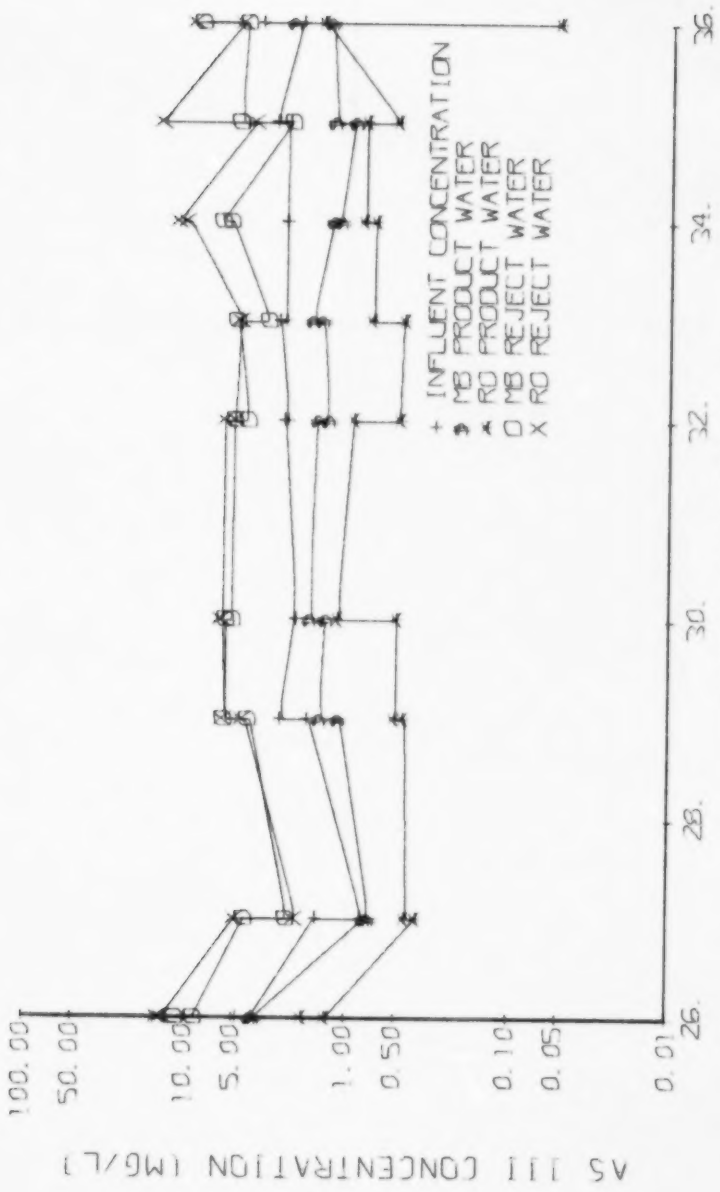


Figure 9. Arsenic III Removal by Reverse Osmosis Systems

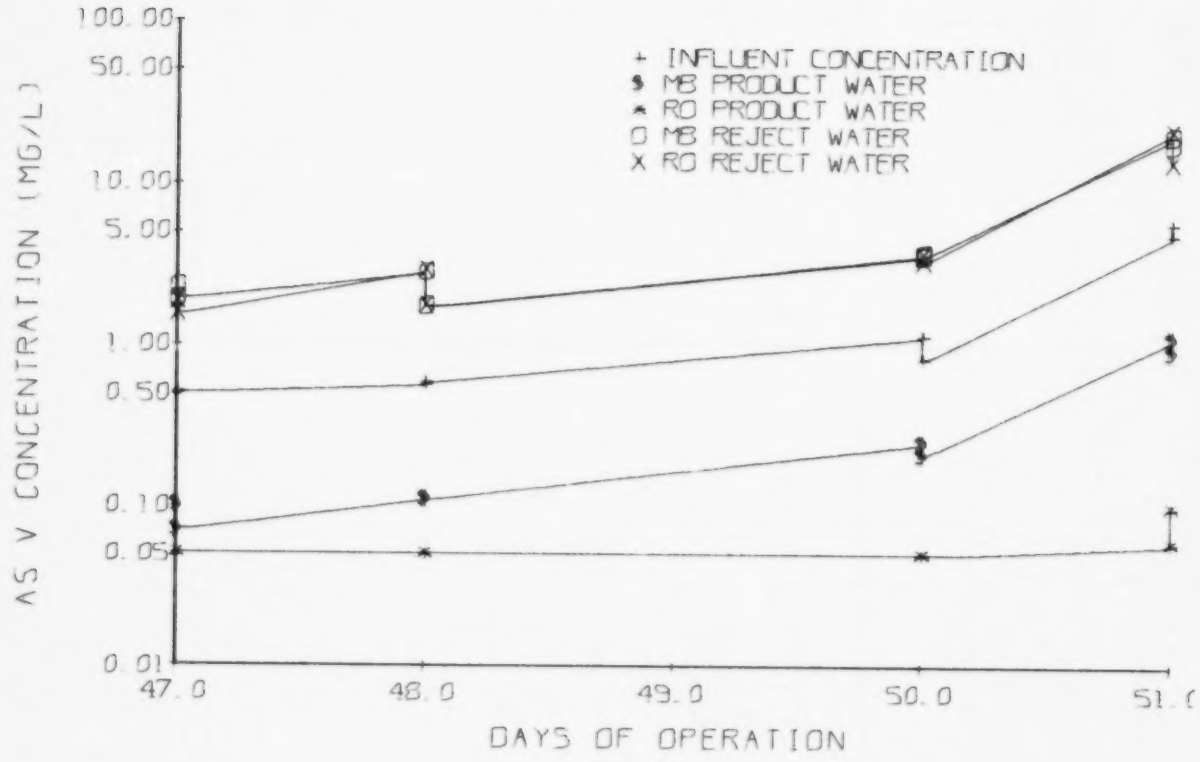


Figure 10. Arsenic V Removal by Reverse Osmosis Systems

OTHER TEST RESULTS

A series of tests were conducted for the removal of selenium as indicated in the test schedule of Table 3. The results of the laboratory analyses of the water samples were inconsistent, which suggested problems with the analyses. Further investigations confirmed that the analytical problems were probably caused by the interference of the high concentrations of either sulfate or chloride or both. Once these problems are solved, the tests will be repeated. Because the data developed were meaningless, none of the results are being reported.

Tests were attempted on a limited basis for the removal of cadmium and lead. Because of the hydrogen sulfide in the feed water, neither cadmium nor lead could be measured in either the feed water or treated water. Precipitation of cadmium sulfide and lead sulfide was assumed to be occurring as soon as the cadmium or lead was introduced into the feed water. Tests for these two elements are planned for the future when a different quality of test water is obtained.

The feed water was analyzed for Ra-226 because it has been found in many of the ground waters in the Sarasota County, Florida area. Because of the high cost for Radium analyses and because data on the removal of Radium-226 has been extensively studied,[9] only one set of grab samples were analyzed. The results of these tests are given in Table 9.

TABLE 9. Radium-226 Removal by Pilot Plant Systems

Sample	Radium-226 Concentration PCi/L + 2 error	Percent Removal
Feed Water	16.9 ± 0.8	
RO Product	0.44 ± 0.02	97.4
RO Reject	65.2 ± 2.2	
MB Product	6.47 ± 0.13	61.7
MB Reject	66.8 ± 2.3	

These results show excellent removal (97.4 percent) by the high pressure RO system and moderate removal (61.7 percent) by the low pressure MB.

SECTION 6

DISCUSSION

REVERSE OSMOSIS SYSTEMS

Several problems were encountered during the reporting period, but none of them could be attributed to the performance of the systems themselves. The initial problem of reduced pressure and flow during the first nineteen days was caused by the raw water feed system. Thus, during this time, both systems operated at less than design pressure and flow. Also, several problems were encountered with four of the conductivity meters.

The second and more significant problem of membrane fouling was never really solved. Initially, bacterial contamination was suspected to be the cause, however, this type of problem generally results in the deterioration of a cellulose membrane with a decrease in rejection capability. Test data show that just the opposite occurred; the membranes became tighter, thereby increasing rejection and reducing flux. The yellow-brown precipitate found in the reject water samples was not identified although the microscope examination suggested that it might have been biological in nature.

The membrane fouling did not present any serious problem to the testing program. The fouling problem did, however, cause some frustration, extra expense and delayed the test program by several months. Also, the modified systems operated at less than design flows and at two different rates instead of identical rates as originally planned. Nevertheless, the project continued and meaningful data were developed.

Although the systems operated under three different sets of conditions, the systems performed steadily during each period. The instrumentation indicated that both systems operated near the design recovery rate of 75 percent and several recent checks of the flow meters suggest that actual recoveries may have been slightly higher than recorded. If this is the case, recorded rejections of contaminants and natural constituents measured should be higher with an actual recovery rate of 75 percent.

Percent rejection of the two systems, as measured by conductivity, changed only slightly each time the systems were modified. During the initial nineteen days of reduced flows and pressures, RO rejection was 94.6 percent (265 psig) and MB rejection was 47.6 percent (163 psig). When the pressures were increased (RO-339 to 359; MB-184 to 187) RO rejections decreased by less than 1 percent and MB rejection decreased by 3 to 4 percent. These data (Table 4) suggest, therefore, that both systems were

performing as designed; the high pressure RO system achieved nominal rejections of near 95 percent and the low pressure MB system near 45 percent.

CONTAMINANT REMOVAL

A summary of the removal data for the natural substances in the feed water (Table 5) shows, first, that although some differences exist between the two sets of chemical measurements by CHWA and EQL, the differences are consistent and thus the rejection calculations of each set of data are very comparable. Except for the TDS rejections by both systems during the 28-69 test run period, the calculated rejections for the natural substances for the two systems were within 1 to 3 percentage points. Differences in TDS measurements were expected because of the differences in the analytical method used by each lab.

A comparison of the data from the three test periods shows that the changes in operating conditions, including pressure, did not significantly effect the rejection percents during the three periods. Excluding color and TOC readings, rejections of the natural constituents measured were within about three percentage points. This suggests, therefore, that removals of the spike contaminants can be compared under the operating conditions imposed. Significant changes in pressure and recovery rates would, however, effect the rejection characteristics of both systems.

Test data for color and TOC show major differences in rejections during the three test periods. Little signficance is attached to these differences because the color of the feed water was effected by the contaminant spike and because of a wide variation in TOC measurements of the feed water. Several unanswered questions have also been raised regarding the high TOC readings of the ground water. Work is being done to confirm these high values and until this work is completed, no conclusions can be drawn.

Removal data of the natural substances clearly demonsrates the differences in the capabilities of the low and high pressure systems. Rejections for the high pressure RO system ranged from a low of 87.7 percent (sodium) to a high of 99.4 percent (sulfate). The low pressure MB system achieved much lower rejections, ranging from 36.1 percent (sodium) to 85.8 percent (sulfate). These data also show that rejections by each system vary with the specific substance with the rejection range for the MB being much wider than that for the RO system (Fig 11). The order of removal by substance from best to worst was about the same for both systems, however. Highest rejections by each system were achieved with sulfate and lowest with sodium. All of these results are consistent with the results of the data report by Sorg from the RO systems reported upon in Sarasota County, Florida.[9]

Removal of specific contaminants by the two systems varied with the contaminant tested as summarized in the following tabulation:

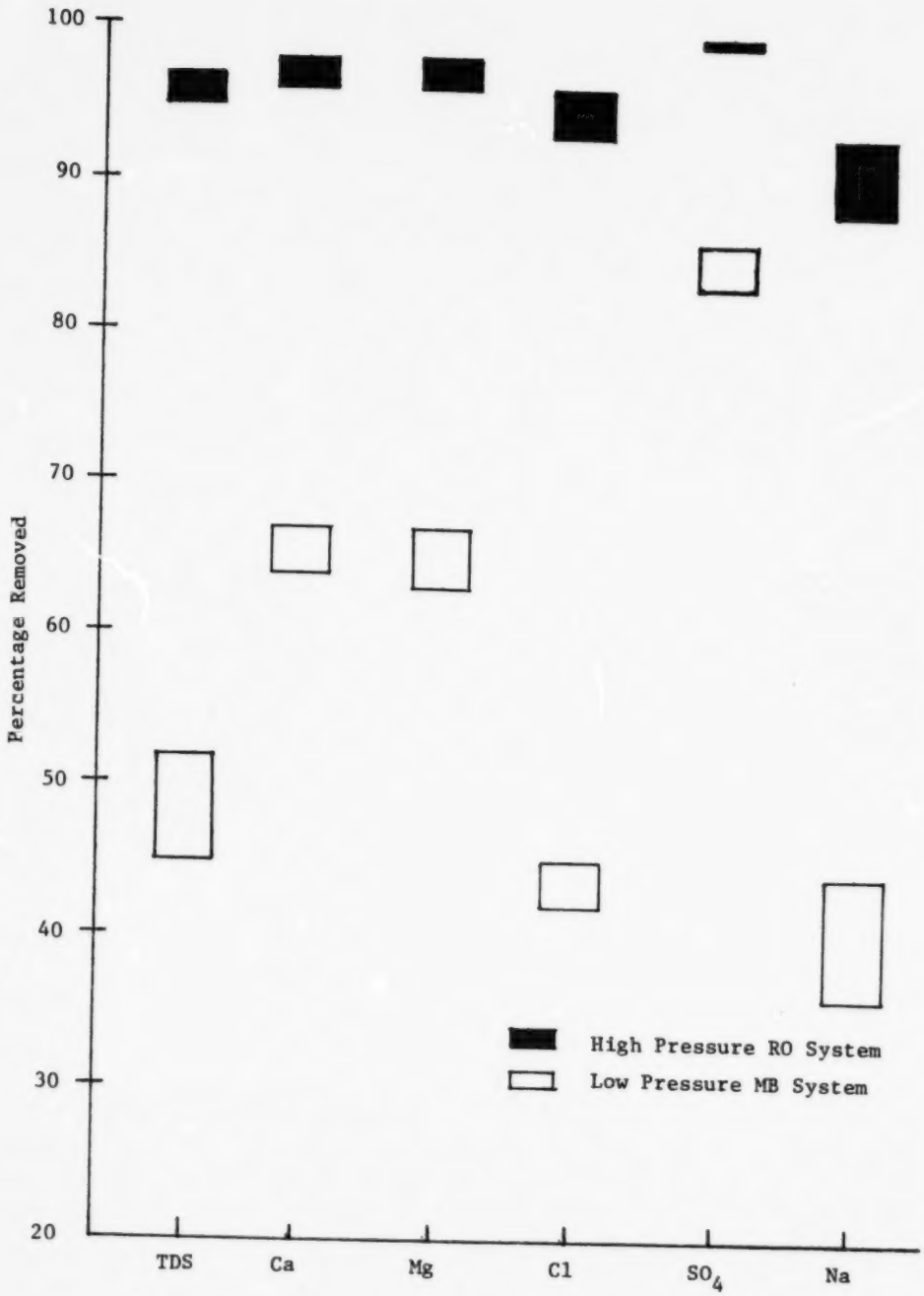


Figure 11. Removal of Natural Constitutents from Feed Water

TABLE 10. Summary of Contaminant Removal Results

Contaminant	Percentage Removed	
	RO System	MB System
Fluoride	90.3 - 93.4	57.9 - 62.4
Nitrate	75.7 - 80.0	6.0 - 24.5
Arsenic III	63.1 - 69.8	11.9 - 35.4
Arsenic V	95.0 - 98.5	77.0 - 80.6

As expected, the high pressure, high rejection RO system clearly outperformed the low pressure, low rejection MB system. Although rejections were significantly different between the two systems, the order of removal effectiveness of the four contaminants was about the same: Arsenic V, fluoride, arsenic III, nitrate for the MB system and Arsenic V, fluoride, nitrate and Arsenic III for the RO system. Data also showed that on a percentage basis, removal was not influenced by the initial concentration (Fig. 12).

Although the low pressure MB system requires about half the energy (11 amps) as the high pressure system (22 amps), rejection efficiency for the contaminants is such that the system could only be considered when the contaminant concentrations exceed the MCL by only a small factor. The maximum feed water concentration for which each system can achieve the MCL's given in Table 11 can be determined from the average percentage removal values.

TABLE 11. Estimate of Maximum Concentration of Contaminants to Achieve MCL by RO Systems

Contaminant (MCL Concentrations mg/L)	Estimated Maximum Concentration (Mg/L) in Feed Water for System to Achieve MCL	
	RO System	MB System
Fluoride (1.4)	14	3.6
(2.4)	26	6
Nitrate (10)	46	14
Arsenic III (0.05)	0.2	0.09
Arsenic V (0.05)	1.0	0.24

Unlike most other treatment methods, reverse osmosis can be an effective treatment method for almost all contaminants. The primary advantages for the application of this technique is for the treatment of water supplies having several contaminants that would require a combination of other treatment methods; and for water supplies having one or more contaminants along with high total dissolved solids. If the quality of the raw water is such that a high percent of removal is not required, then the low pressure system can be considered as an economic alternative.

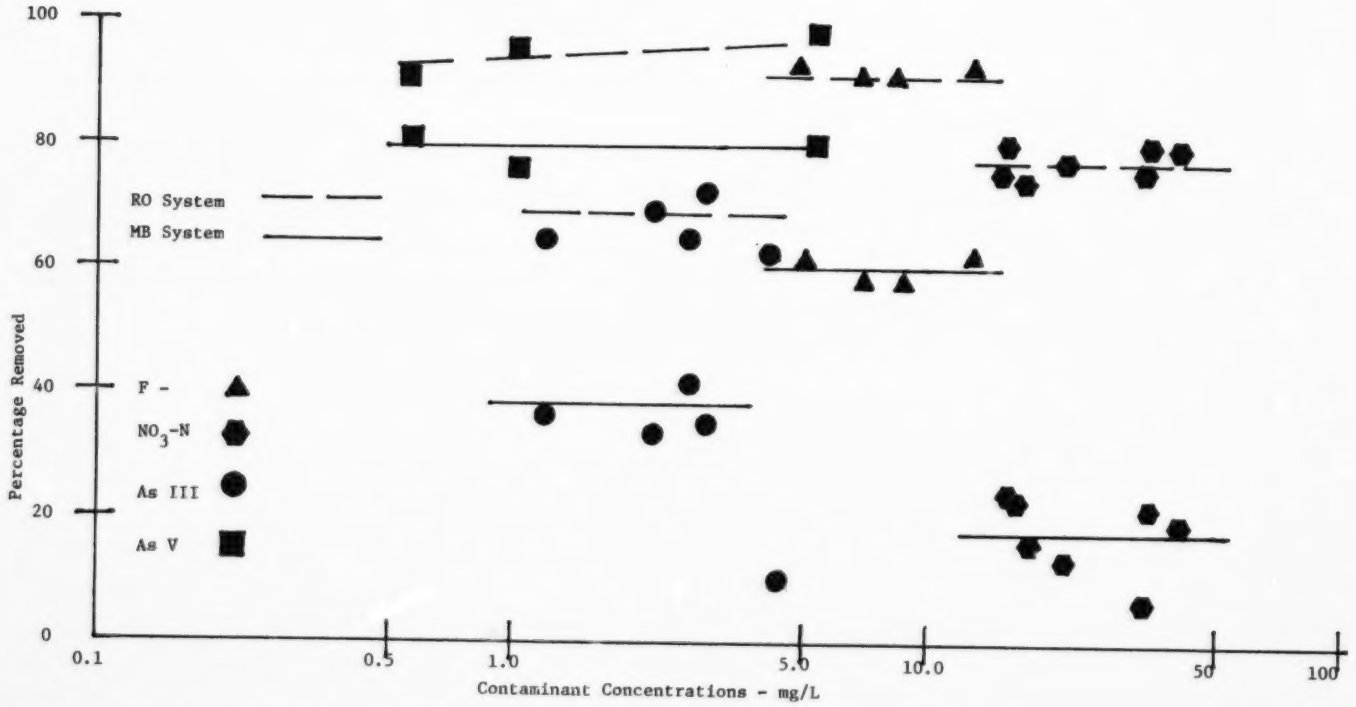


Figure 12 - Removal of Inorganic Contaminants by Low and High Pressure RO Systems

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APPENDIX A. SYSTEM PERFORMANCE DATA RECORDING FORM

Day (1)	Day (2)	Time	Date	System Code	Feed Pressure	Feed pH	Feed Temp.	Feed Conductivity	Product Conductivity	Product Pressure	Product Flow	Reject Conductivity	Reject Pressure	Reject Flow	Reject pH	Filter Inlet Pressure	Filter Outlet Pressure	Filter Cartridge	DM Filter	Amps	Volt Code	Total Flow Reading	Hours of Operation	Product Water Disposal	Deepwell ET-Rte.	Shallow Wells Hours	DM Δ PSI	Base Δ PSI

APPENDIX B.

DESCRIPTION OF MEMBRANE FOULING PROBLEM AND CLEANING PROCEDURES

MEMBRANE FOULING PROBLEM

Throughout the nitrate testing period (11-25 test run days), the differential pressure between the feed water and reject water rose slowly, but steadily, from 38 psig to 75 psig. Proceeding cautiously, the testing program was continued with arsenic (III). The differential pressure continued to increase after three days and a yellow-brown substance was found in the reject water samples. At this point, the decision was made to stop testing and try to reduce the differential pressure by chemically cleaning and flushing the membranes.

A microscopic examination (1250X) of the yellow-brown substance by EQL suggested the material might be bacteriological because of the lack of a consistent morphology. Assuming, therefore, that the fouling substance was organic in nature, a standard cleaning solution "B" recommended by the membrane manufacturer, Fluid Systems, Inc., for organic foulants was selected as the cleaning solution. This solution was made up by adding the following to 45 gallons of water and adjusting the solution to pH 6.0 with sulfuric acid:

chemical	amount
Sodium Tripolyphosphate	7.5 lb
Sodium EDTA (powder)	3.0 lb
Carboxy methyl cellulose	2.5 g
Triton x-100 (Rohm & Haas)	175.0 mL
Formaldehyde (36 percent formalin)	2,365.0 mL

Before cleaning the MB system, the system was flushed with raw feedwater at reduced pressure and twice the normal reject velocity to remove as much of the foulant as possible. The cleaning solution was then recirculated through the first stage of the MB system at 3 gpm per shell at 75° F for 60 minutes. The recommend flow rate, 0.3 to 0.4 L/S (5 to 7 gpm), could not be achieved by the pump and no heating equipment was available to raise the temperature of the cleaning solution to a recommended level of 120°F.

After cleaning, the system was flushed again and then restarted. The changes in operating characteristics are as follows:

Parameter	Before Cleaning	After Cleaning
Recovery	75 percent	75 percent
Feed pressure	190 psig	190 psig
Product flow	1.98 L/S (31.5 gpm)	1.64 L/S (26 gpm)
Reject flow	0.66 L/S (10.4 gpm)	1.54 L/S (8.4 gpm)
Feed conductivity	1900 umhos	1850 umhos
Product Conductivity	900 umhos	720 umhos
Differential Pressure (1st stage)	35 psig	35 psig

Whereas this cleaning procedure did not lower the differential pressure, there was an unexpected drop in product water flow and an increase in rejection percent from 52.6 to 61. Fluid Systems, Inc. was consulted again and the recommendation was made to repeat the cleaning procedure with their standard solution "A" used for inorganic foulants such as iron or heavy metals. This solution was made up by adding the following to 45 gallons of water and adjusting the solution to pH 3.0 with ammonium hydroxide:

Chemical	Amount
Citric Acid	7.5 lb
Triton X-100 (Rohm & Haas)	175 mL
Carboxy methyl cellulose	2.5 gm

This cleaning solution was recirculated through the first stage again at 3 gpm and at an average temperature of 75°F for 60 minutes. Once again, the cleaning process showed an unexpected additional drop in product water flow to 1.29 L/S (20.5 gpm) and an additional increase in rejection. A comparison of the product water conductivity measurements of each MB first stage vessel is as follows:

	Product Water Conductivity (umhos)	
1st Stage Shell No.	After Solution "B" cleaning	After Solution "A" cleaning
4	320	230
5	300	200
6	320	220
7	300	200
11	520	370
12	480	310
13	480	320
14	500	320

Because the two cleaning procedures did not achieve the desired reduction of differential pressure and actually changed the membranes characteristics, a decision was made to run the unit for 48 hours under normal operating conditions (pH 5.4 to 5.8). The results of this step are shown below:

Shell No.	Product water conductivity (umhos)
1st stage	
4	260
5	220
6	220
7	220
11	400
12	340
13	340
14	330
2nd stage	
2	800
3	860
9	1300
10	1200

Fluid Systems, Inc. was again consulted and a recommendation was received to clean the second stage of the MB system with solution "B". Because of the smaller number of shells, the cleaning feed rate was 0.4 L/S (6 gpm) per shell. Some equipment was also obtained to raise the solution temperature to 111°F. The solution was circulated for 60 minutes during which time the temperature dropped to 95°F.

After cleaning, the system was operated and once again, the results were essentially the same; the product water conductivity readings (umhos) from the second stage shells were 800 (#2), 840 (#3), 1200 (#9) and 1050 (#10). Furthermore, product water flow did not increase and remained at 1.45 L/S (23 gpm) at the feed pressure of 190 psig.

Because of the complete lack of success of the cleaning procedures to restore the membranes to their original characteristics and with no additional hope to correct the problem, the membrane elements were replaced.

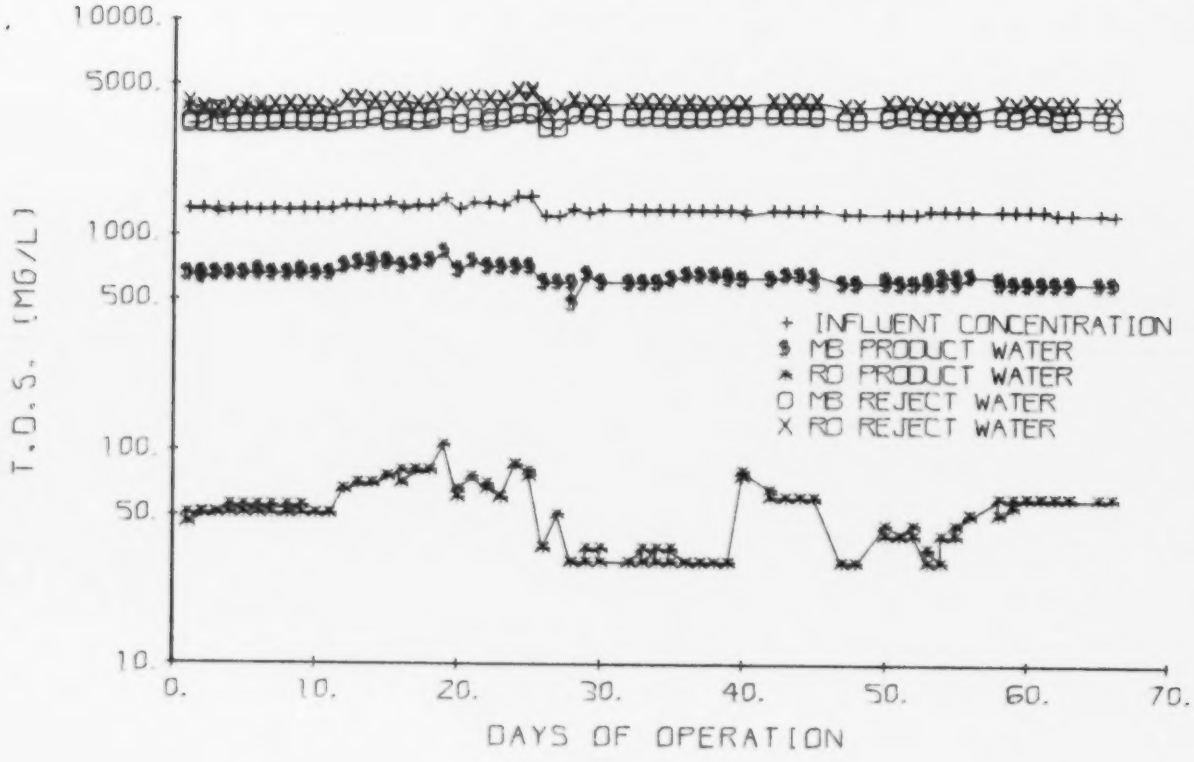

Figure C-1. Total Dissolved Solids Removal by RO Systems (CHWA)

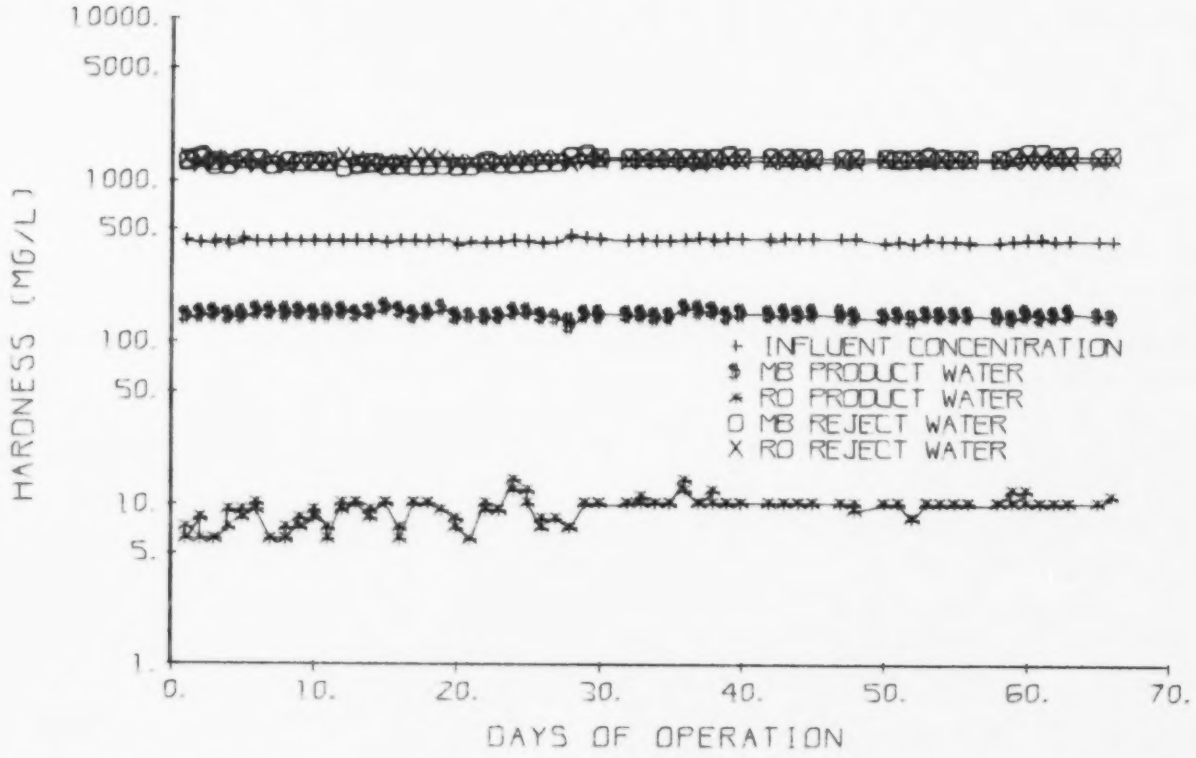

Figure C-2. Hardness Removal by RO Systems (CHWA)

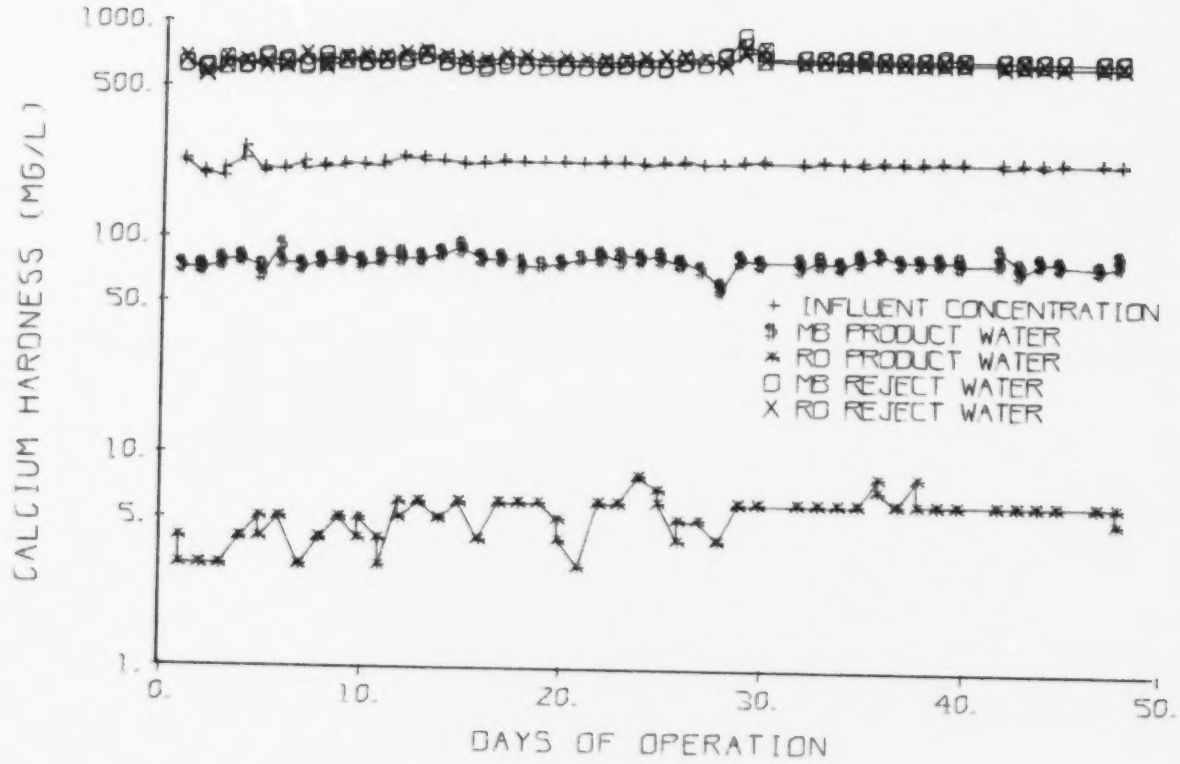

Figure C-3. Calcium Removal by RO Systems (CHWA)

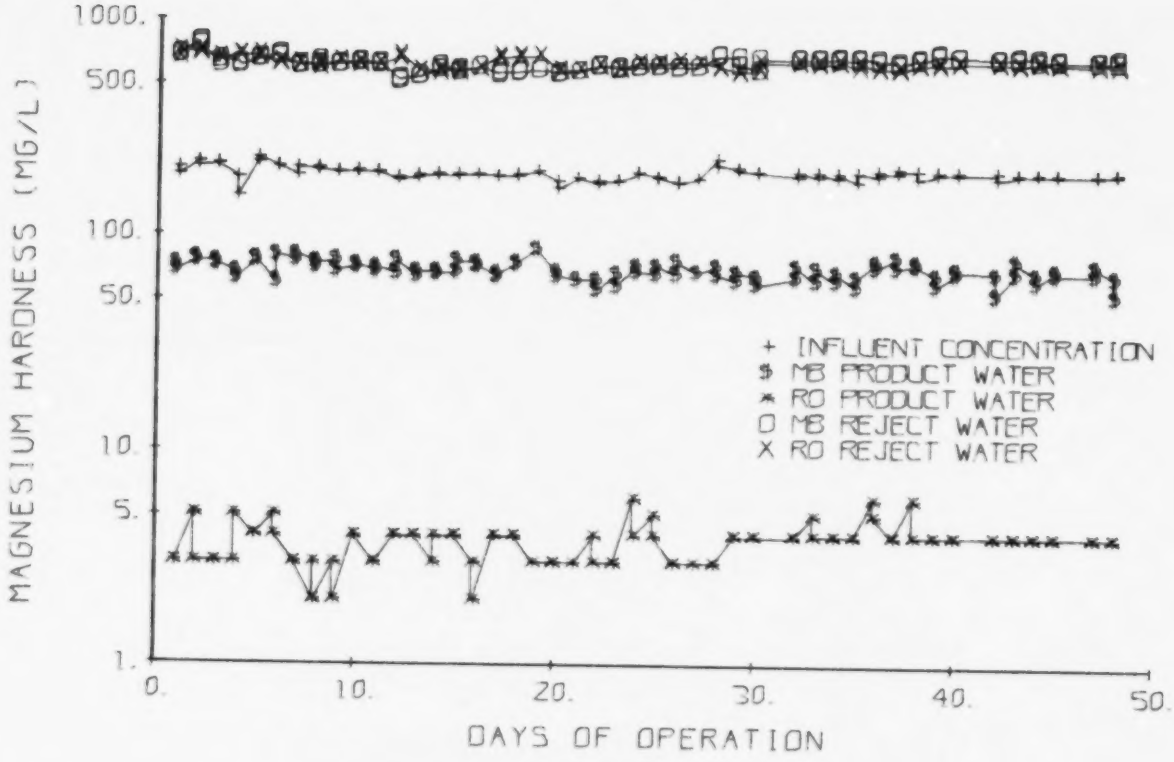

Figure C-4. Magnesium Removal by RO Systems (CHWA)

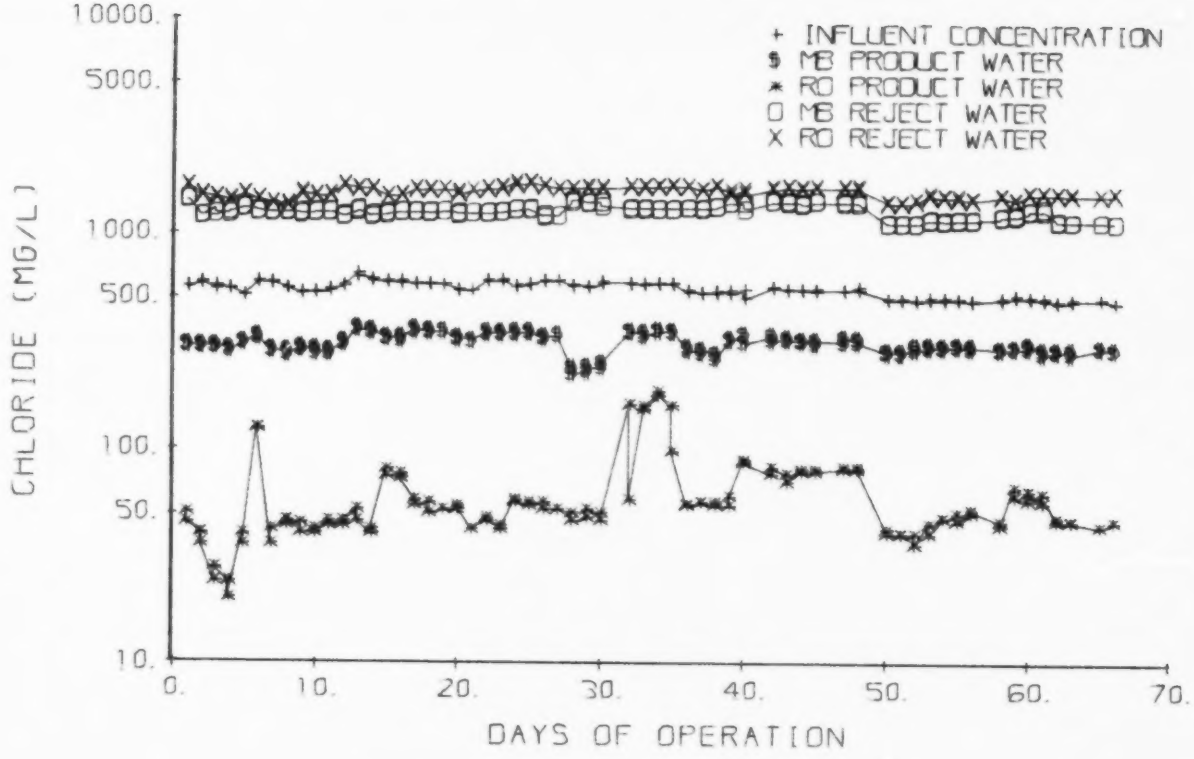

Figure C-5. Chloride Removal by RO Systems (CHWA)

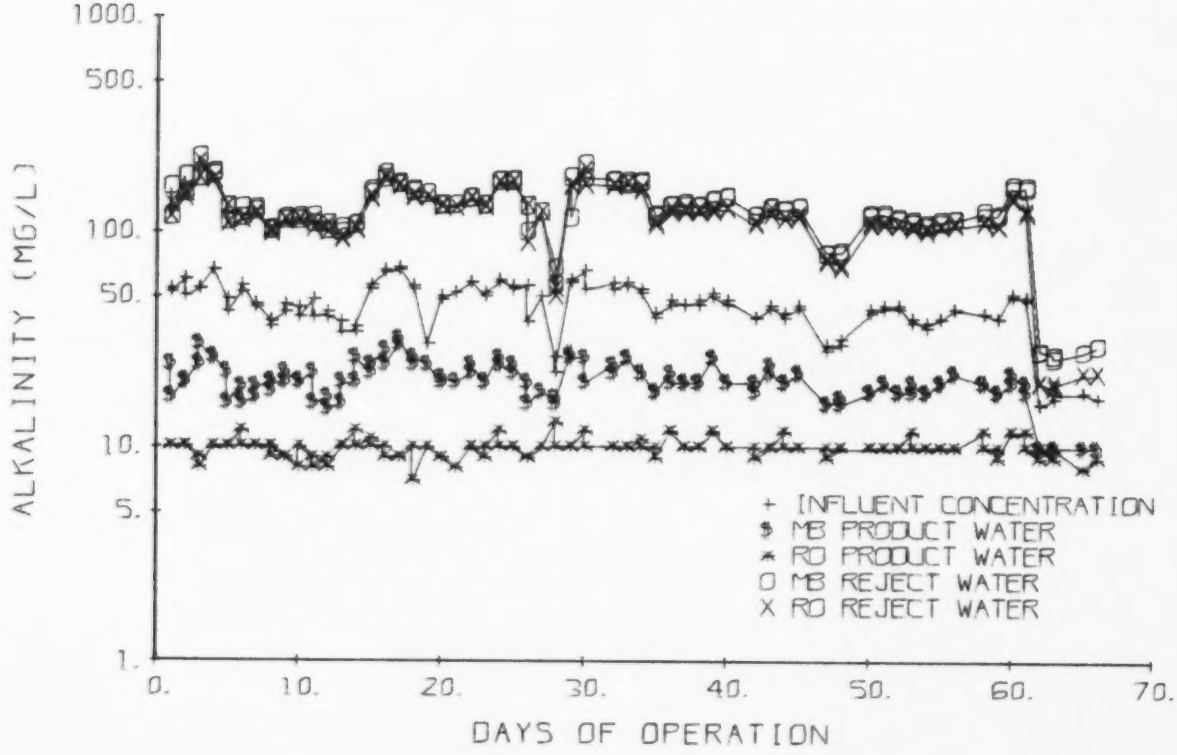

Figure C-6. Alkalinity Removal by RO Systems (CHWA)

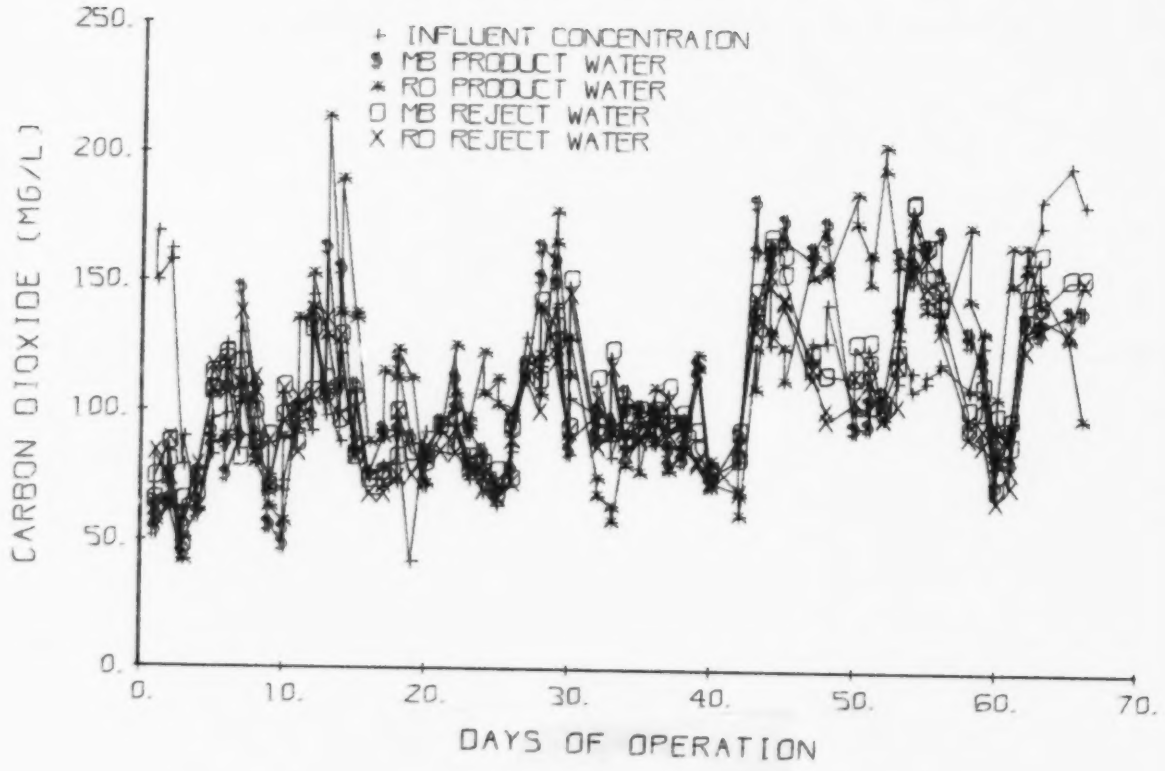

Figure C-7. Carbon Dioxide Concentration in RO System Waters (CHWA)

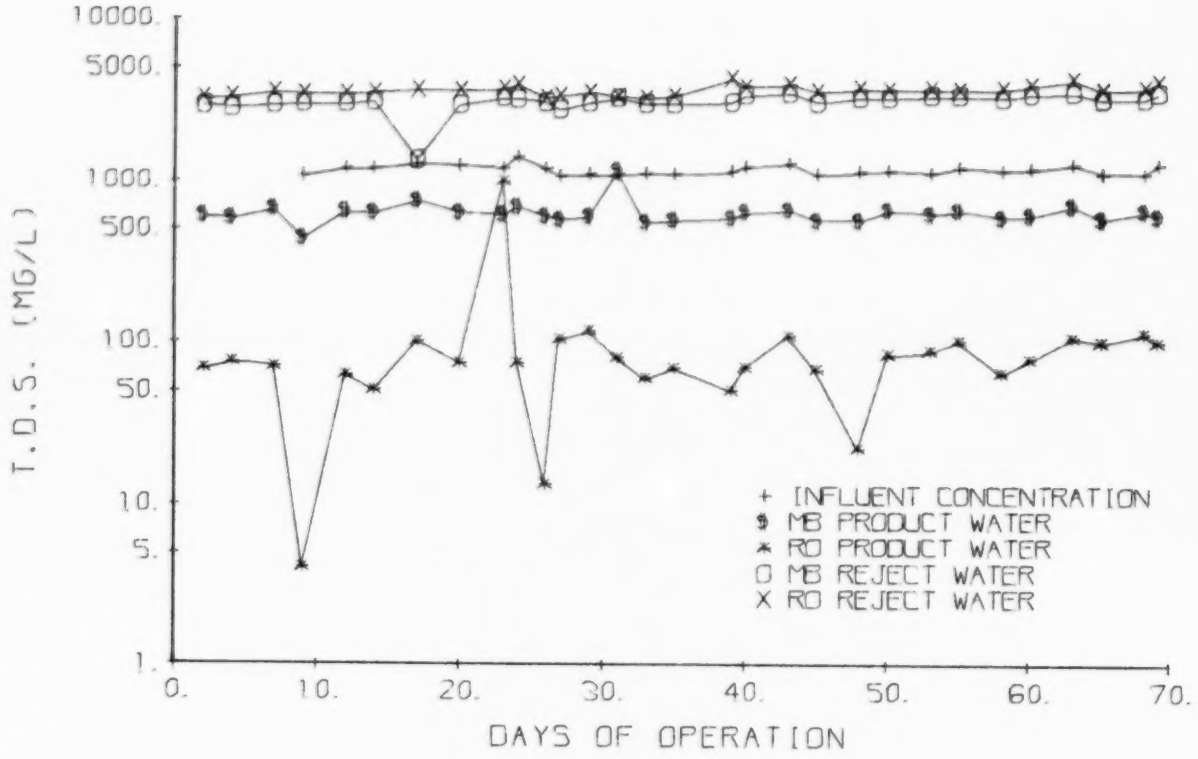

Figure C-8. Total Dissolved Solids Removal by RO Systems (EQL)

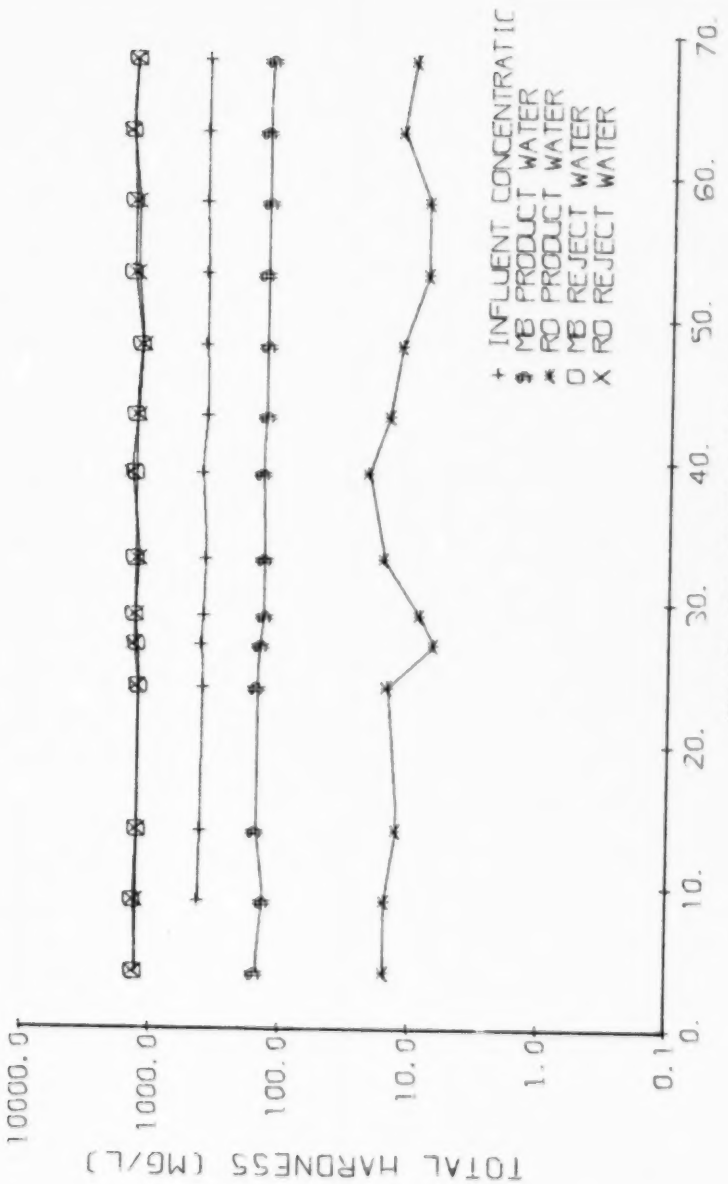

Figure C-9. Hardness Removal by RO Systems (EQL)

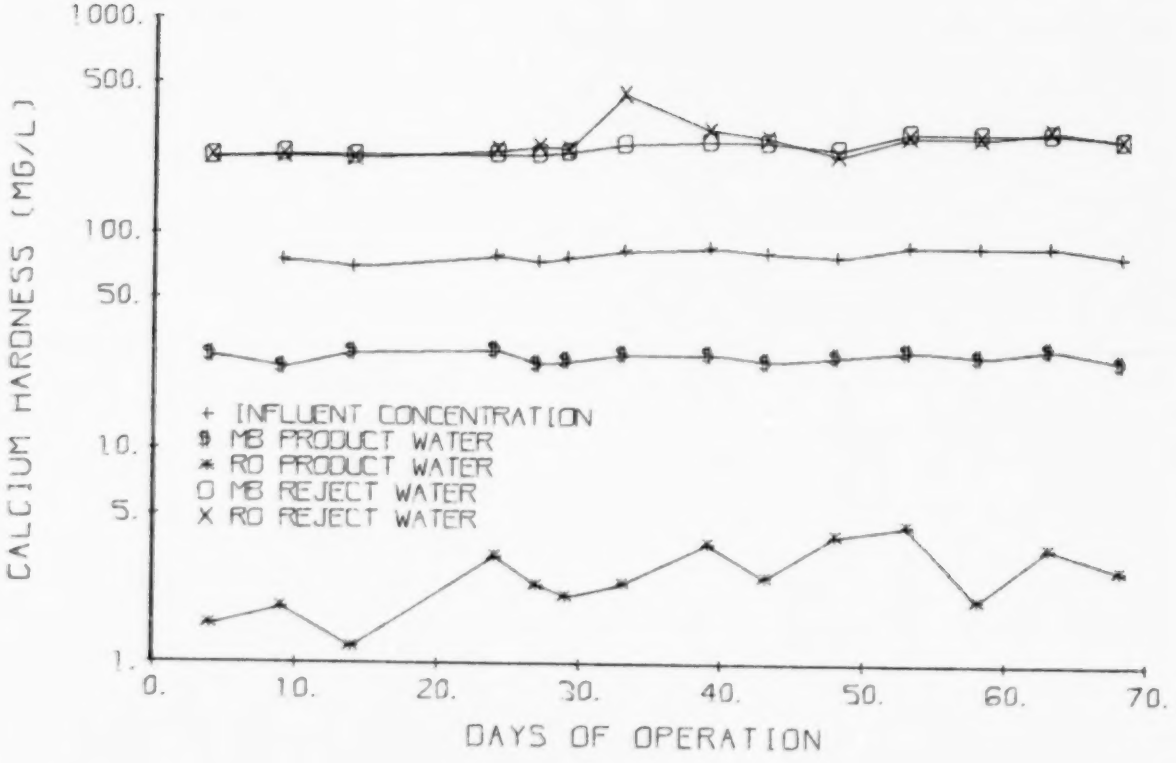

Figure C-10. Calcium Removal by RO Systems (EQL)

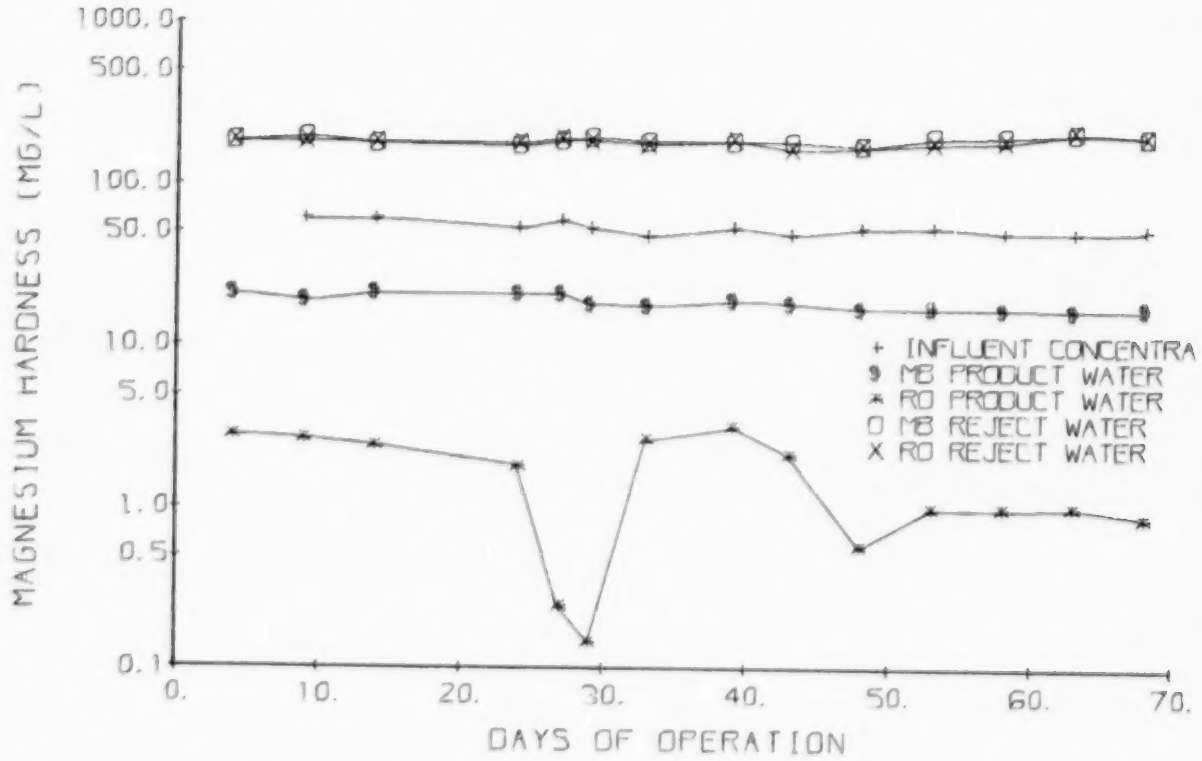

Figure C-11. Magnesium Removal by RO Systems (EQL)

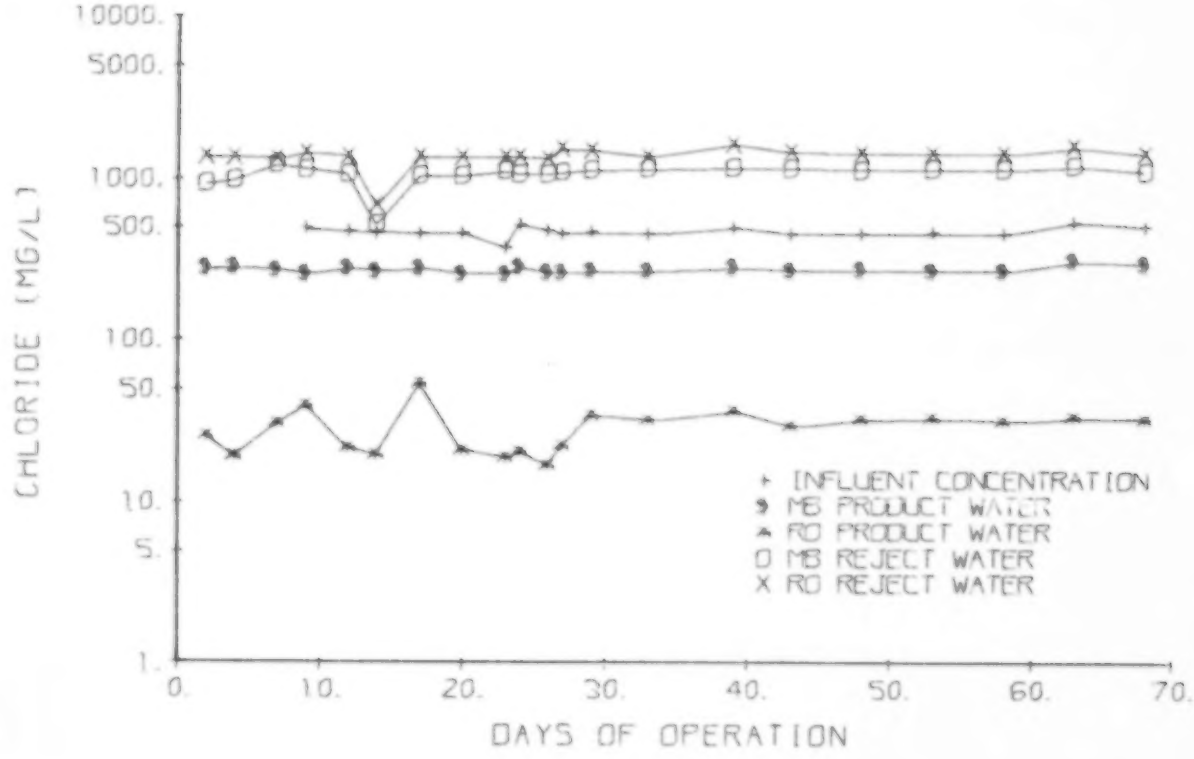

Figure C-12. Chloride Removal by RO Systems (EQL)

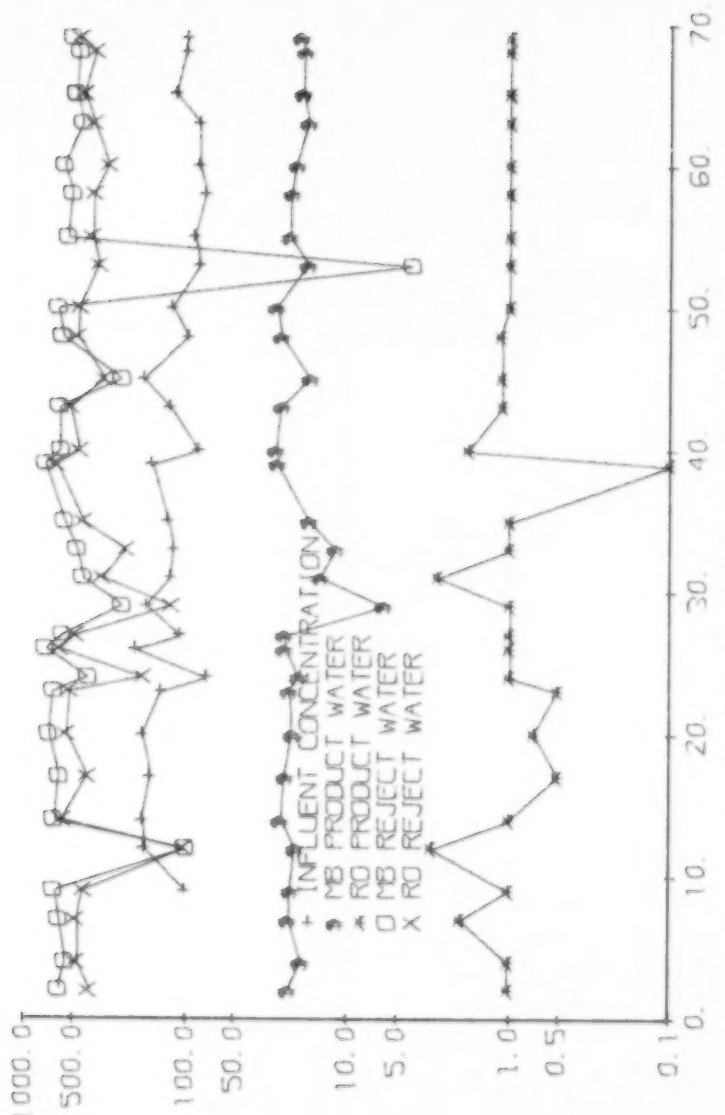

Figure C-13. Sulfate Removal by RO Systems (EQL)

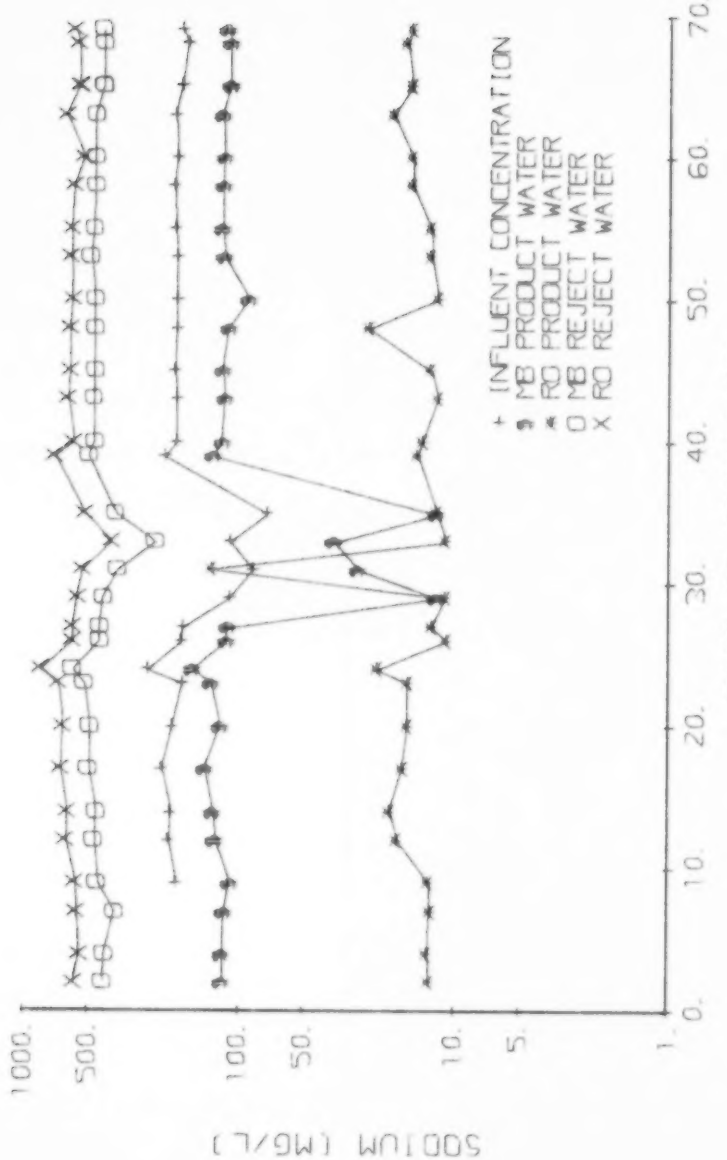

Figure C-14. Sodium Removal by RO Systems (EQL)

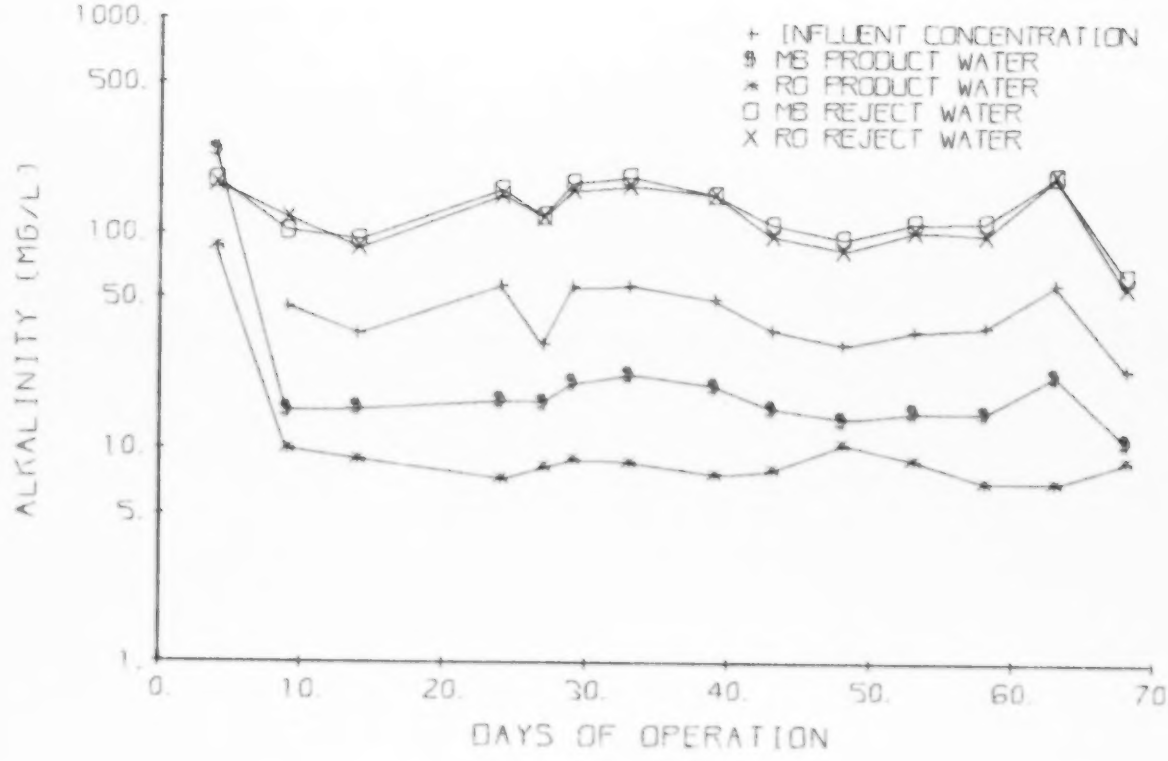

Figure C-15. Alkalinity Removal by RO Systems (EQL)

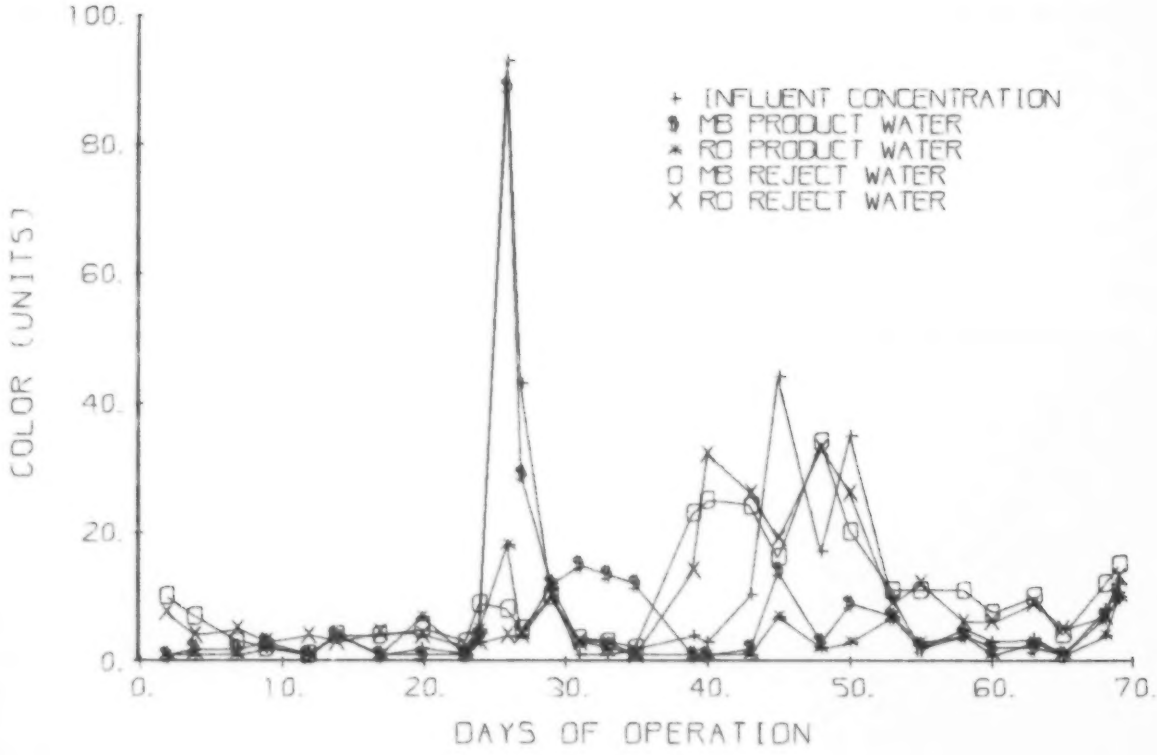

Figure C-16. Color Removal by RO Systems (EQL)

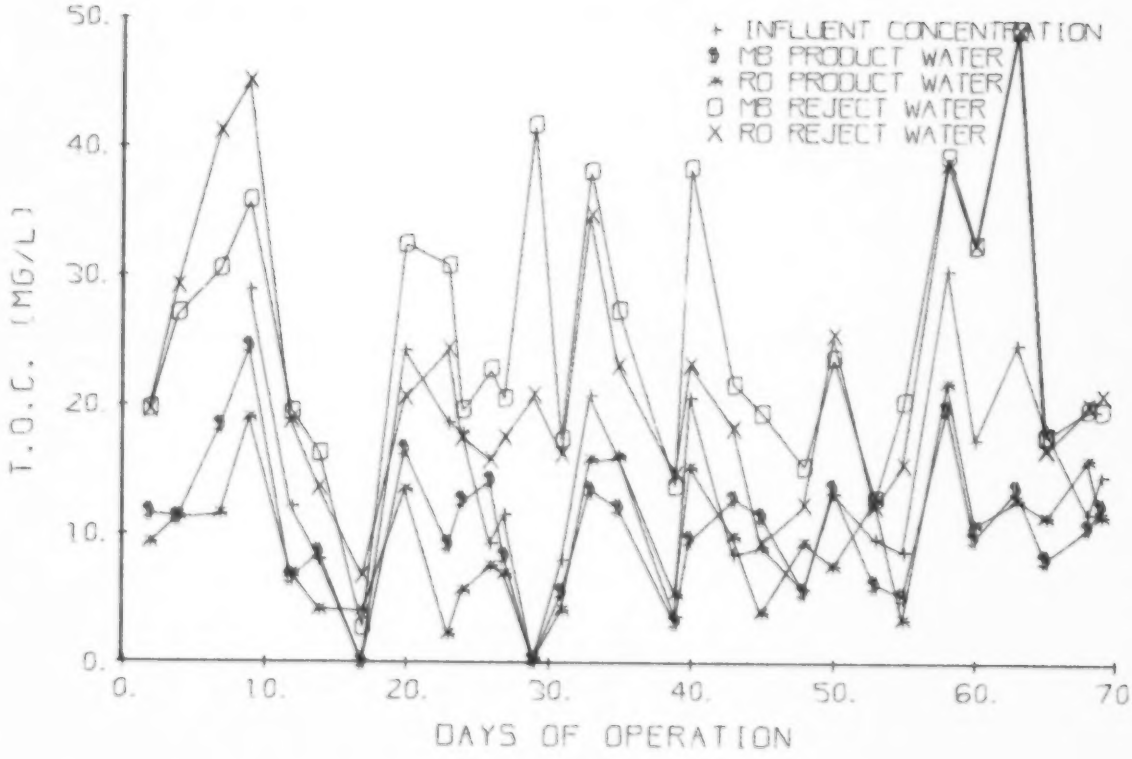

Figure C-17. Total Organic Carbon Removal by RO Systems (EQL)